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13. ABSTRACT (Maximum 200 words)

The first phase of the program was dedicated to improving the cathode heater to be mounted on the thruster, and to integrating the thruster with test equipment already available at CS. A more exhaustive description of this phase of the program was given in the review report number 1. The experimental activity of the second phase was performed in two steps: firstly the calibration of the gas feeding system was conducted, then the measurements of the electrical characteristics with cold cathode and with the cathode heated at about 2100K at the tip were taken. Argon, nitrogen, hydrogen and gas mixtures simulating hydrazine and ammonia were used as propellants.

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High Cathode Temperature Experiments on an MPD Thruster

Final Report

February 1995

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Foreword

This report describes the activities carried out at CENTROSPAZIO (CS) in the framework of the AFOSR special contract no. SPC-93-4051, "High Cathode Temperature Experiments on an MPD Thruster".

As illustrated in the relevant technical and administrative proposal, the first phase of the programme was dedicated to improving the cathode heater to be mounted on the thruster, and to integrating the thruster with test equipment already available at CS. Section 1 briefly describes the activity carried out in the first phase of this programme. A more exhaustive description of this phase of the programme was given in the review report no 1. The thermal analysis of the thruster is described in Appendix 1.

The experimental activity of the second phase was performed in two steps: firstly, the calibration of the gas feeding system was conducted, then the measurements of the electrical characteristics with cold cathode and with the cathode heated at about 2100 K at the tip were taken. Argon, nitrogen, hydrogen and gas mixtures simulating hydrazine and ammonia were used as propellants.

The results illustrated were gathered using a thruster with a modified injection plate in respect to the one described in the review report no 1. This modification (which delayed the conclusion of this contract) is illustrated in Section 2.

The procedure and results of the gas feeding system calibration as well as the procedure adopted for electrical characteristic measurements are described in Section 3 and Section 4 respectively.

Section 5 provides a description and a brief discussion of the results obtained with and without cathode heating for 1 g/s of nitrogen, 0.3 g/s of hydrogen, 1 g/s of simulated hydrazine, 1 g/s of simulated ammonia and 1 g/s of argon.

Finally, Section 6 gives a series of conclusions on the activity and indicates possible developments.

Appendix 2 briefly illustrates the experimental equipment available at CS for MPD testing.

Sec. 1 - Thruster Design

Requirements. NASA Lewis provided CS with the components of two thrusters, as well as two pieces of boron nitride and a thoriated tungsten bar. The devices supplied are normally tested at NASA Lewis as gas-fed, continuous MPD thrusters with an external magnetic field, operating in a power range of 100 - 200 kW. The electrodes are water cooled during operation.

The new thruster was designed in compliance with the following requirements:

• the thruster had to originate from the one supplied by NASA Lewis; the components delivered could be included in the new thruster without limitations, in line with the requirements of the activity;

• the cathode heater had to allow the cathode tip to reach temperatures ranging from 300 K to 2500 K during testing

• the gas feeding system must supply gas pulses with a short transient (few ms) followed by a steady state phase of the mass flow (from 5 to 50 ms), during which the current discharge may occur.

• the thruster had to be easily interfaced with the existing equipment for electrical characteristic measurements and plume diagnostics.

• in view of further activities, the thruster had to be interfaced with the existing thrust stand without significant modifications.

The thruster. In Fig. 1.1 the new thruster is illustrated. It is mounted on a standard, dedicated alluminum flange (12) which acts as an interface with the vacuum chamber IV2 (see appendix 2).

The copper anode (1) was taken from the AFOSR thruster making only slight modifications. Considering the discontinuous operation of the thruster and the thermal analyisis described in appendix 1, no cooling system was adopted for the anode. However, the existing one could be restored easily, if necessary.

The gas is injected by a boron nitride plate located behind the anode (4). The gas flows through eight nozzles manufactured on the plate, while the choking orifices (0.5 mm in diameter) are located on an brass injector (6), behind the plate. The gas is distributed equally to the orifices by an annular volume, manufactured on a brass dispenser (7). The gas is fed to the dispenser by a lateral swagelock (16), to which a teflon tube (from the solenoid valve) is attached (17). All of the contact surfaces between the dispenser, the injector and the plate are sealed with graphite gaskets (5).

A boron nitride insulator (9) fixes the cathode position with respect to the anode. This detail is held in a central position to the plate with a boron nitride spacer (8).

The gas injection group (4, 6, 7) and the details 8 and 9 are held between the aluminum flange (12) and the anode by four copper bars (2). The bars are used to connect the anode to the PFN electrically and are isolated from the flange with teflon bushings (13).

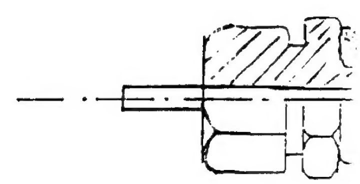
The cathode with the heating system was developed during previous experimental activity on ESA contracts. This configuration was chosen due to its simplicity and the good operating mode shown in previous testing.

The heating system uses the heat supplied by an electric arc established between an inner electrode and the cathode. This electrode plays the dual role of anode to the internal arc during the heat-up phase and cathode to the thruster during discharge. It is a thoriated tungsten cylindrical element (20 mm in diameter), supported by a rear tungsten bar; the edge of the external surface is hemispherical. A cavity was drilled into the core of this electrode to hold the inner one. The bottom of the cavity is specially shaped to start up the internal

electric arc. A thermal dam was machined onto the inner electrode to reduce its thermal conduction. The inner electrode is a thoriated tungsten stick, 3 mm in diameter, with a sharp conical edge. It is fixed to the boron nitride insulator with a swagelock. Alumina sticks are used to insulate the second electrode in order to avoid arc ignition in undesired sites along the electrode.

The cathode with the heater is placed in component 9 and is held by the boron nitride spacer 22 and an aluminum spacer holder (23).

Thermal expansion and stress. The effect of thermal expansion is limited, considering the relatively low heating of the thruster components and the low linear thermal expansion of the most stressed components (see Appendix 1). Nevertheless, the cathode and the anode are fixed with screws with elastic washers, in order to prevent the thruster from thermal stress or from gaps due to the differential expansion of the components. This function is also partially carried out by the graphite gaskets and the teflon bushings that have a certain elasticity.



N° part.	NAME	N° pieces	MATERIAL	NOTES
26	O - RING	1	NEOPRENE	
25	SCREW M 4X40 UNI 5739-65	6	STAINLESS STEEL	
24	ELASTIC WASHER N° 2	6	C 98 UNI 3545	
23	SPACER HOLDER	1	ALLUMINUM ALLOY	
22	SPACER N° 2	1	H P BORON NITRIDE	
21	GASKET N° 3	1	GRAPHOIL	
20	CATHODE HEATING GROUP	1	Tungten/Allumina/HP Boron Nitride	From previous design
19	NUT N° 3	1	TEFLON	
18	VALVE ADAPTER	1	TEFLON /BRASS	Compound detail
17	TUBE	1	TEFLON	
16	SWAGELOCK	1	STAINLESS STEEL	
15	NUT N° 2	4	STAINLESS STEEL	
14	ELASTIC WASHER N° 1	4	C 98 UNI 3545	
13	BUSH	4	TEFLON	Modified (see Sec. 2)
12	FLANGE	1	ALLUMINUM ALLOY	
11	O-RING	9	NEOPRENE	
10	GASKET N° 2	1	GRAPHOIL	
9	CATHODE INSULATOR	1	HP BORON NITRIDE	
8	SPACER N° 1	1	HP BORON NITRIDE	
7	DISPENSER	1	BRASS	
6	INJECTOR	1	BRASS	Modified (see Sec. 2)
5	GASKET N° 1	4	GRAPHOIL	
4	INJECTION PLATE	1	HP BORON NITRIDE	Modified (see Fig. 2.1)
3	NUT N° 1	4	STAINLESS STEEL	
2	STAY BAR	4	COPPER	
1	ANODE	1	COPPER	

CENTRO SPAZIO	Major Assembly MPD THRUSTER WITH CATHODE HEATING		Project F6170893W0738
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Date: 1/10/95 — Modifications: details 4, 6, 11 — Sign.	Group	Designed	Scale 1:1
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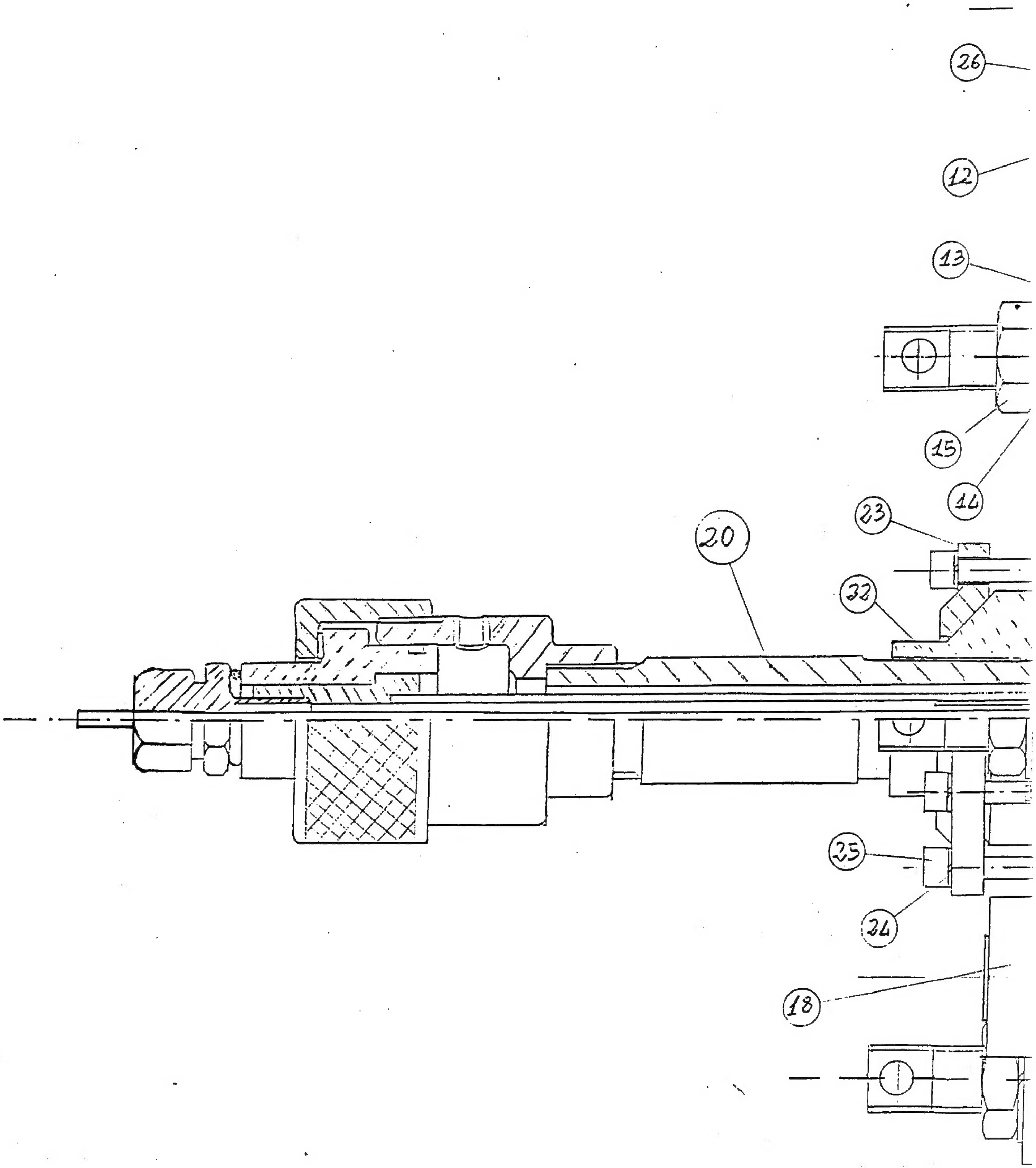

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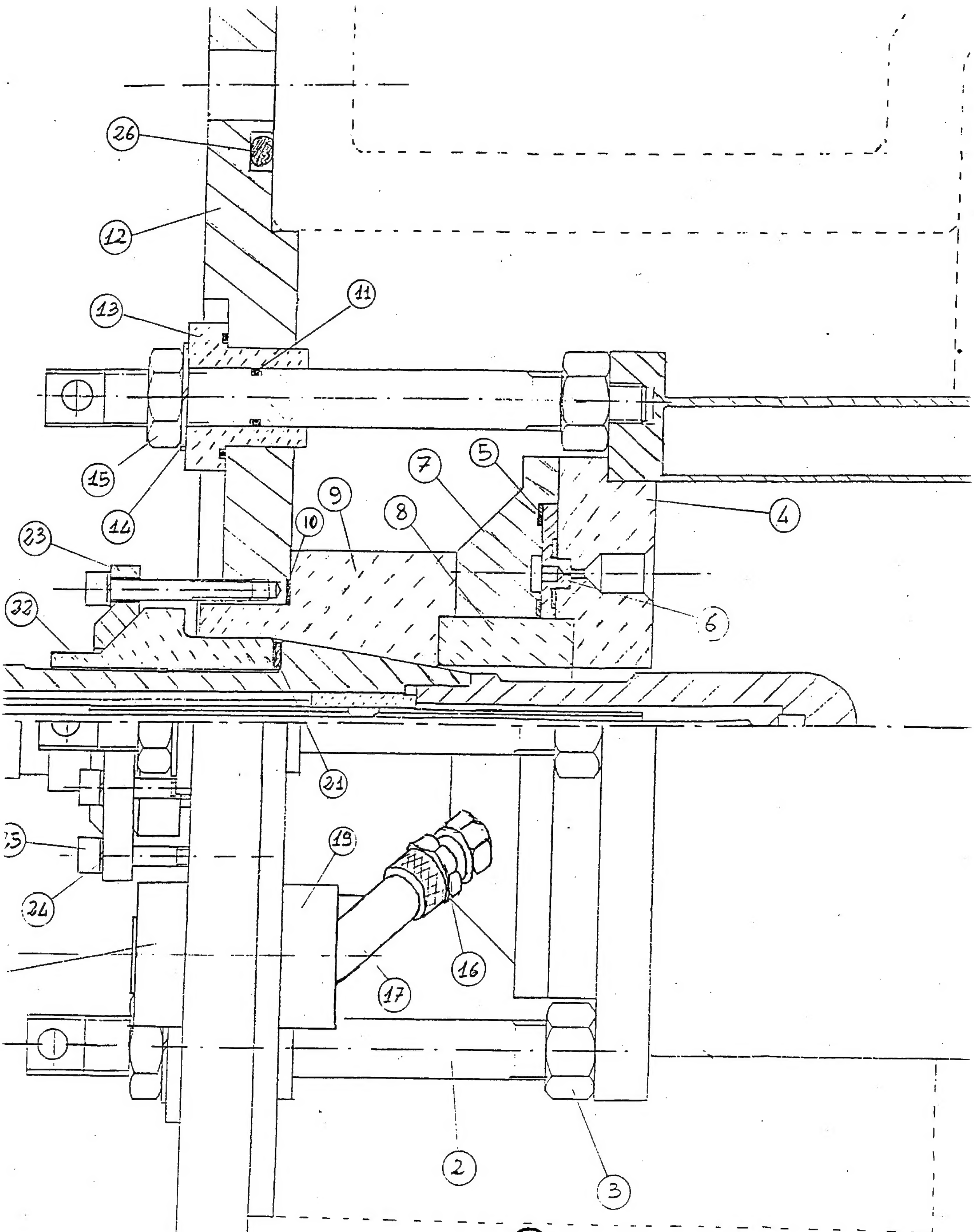

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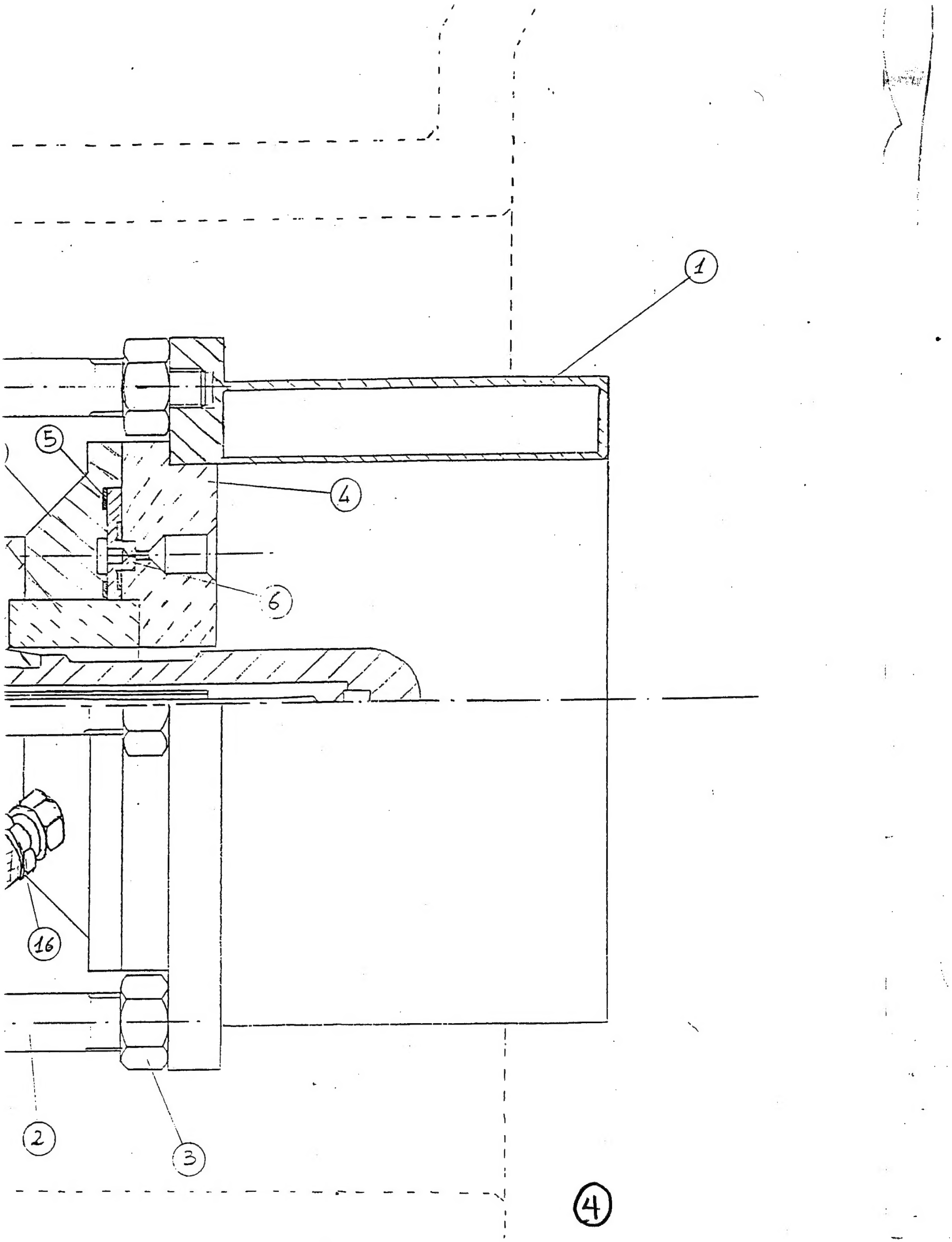

1
5
4
6
16
2
3

Sec. 2 - Thruster Modifications

Preliminary tests carried out with the thruster, as described in Sec. 1 and in review report no. 1 suggested the modification of some of its components. The most significant change was performed on the injection system (details no. 4 and 6). Its previous design consisted of eight orifices equally-spaced along a circumference at half-distance between the cathode and the anode inner surface diameter. This configuration was chosen in analogy with the one adopted on the NASA Lewis thruster for a continuum operation mode. Nevertheless, the ignition procedure usually adopted for other pulsed thrusters at CS was not effective for this gas injection mode. Normally, the discharge occurs when the ignitron is activated and the PFN charging voltage is applied between the anode and the cathode. The gas injection mode adopted supplied too low a propellant flow rate towards the cathode. As a consequence, the discharge occurred only at a quite high PFN charging voltage; this precludes the investigation of low currents and/or low mass flow rates (unless an adequate resistor is placed in series with the thruster in order to limit the current at high PFN charging voltage). This problem could be solved by employing a third electrode to ignite the discharge. However, this solution complicates the experimental apparatus and needs substantial modifications to the thruster.

Therefore, the problem was solved by modifying the gas injection system, as shown in Fig. 2.1 (component no. 4). The new configuration has four new orifices and ducts that permit the injection of the propellant at the cathode root. About 1/3 of the propellant is injected at the cathode root, the rest of it is injected through the previously existing orifices. This modification permitted an effective ignition of the thruster also at low mass flow rates and low PFN charging voltages.

During the preliminary tests, the components no. 11, made from teflon were not sufficiently stiff and suffered creep deformations during cathode heating. For this reason, these components were substituted with others made of a phenolic material.

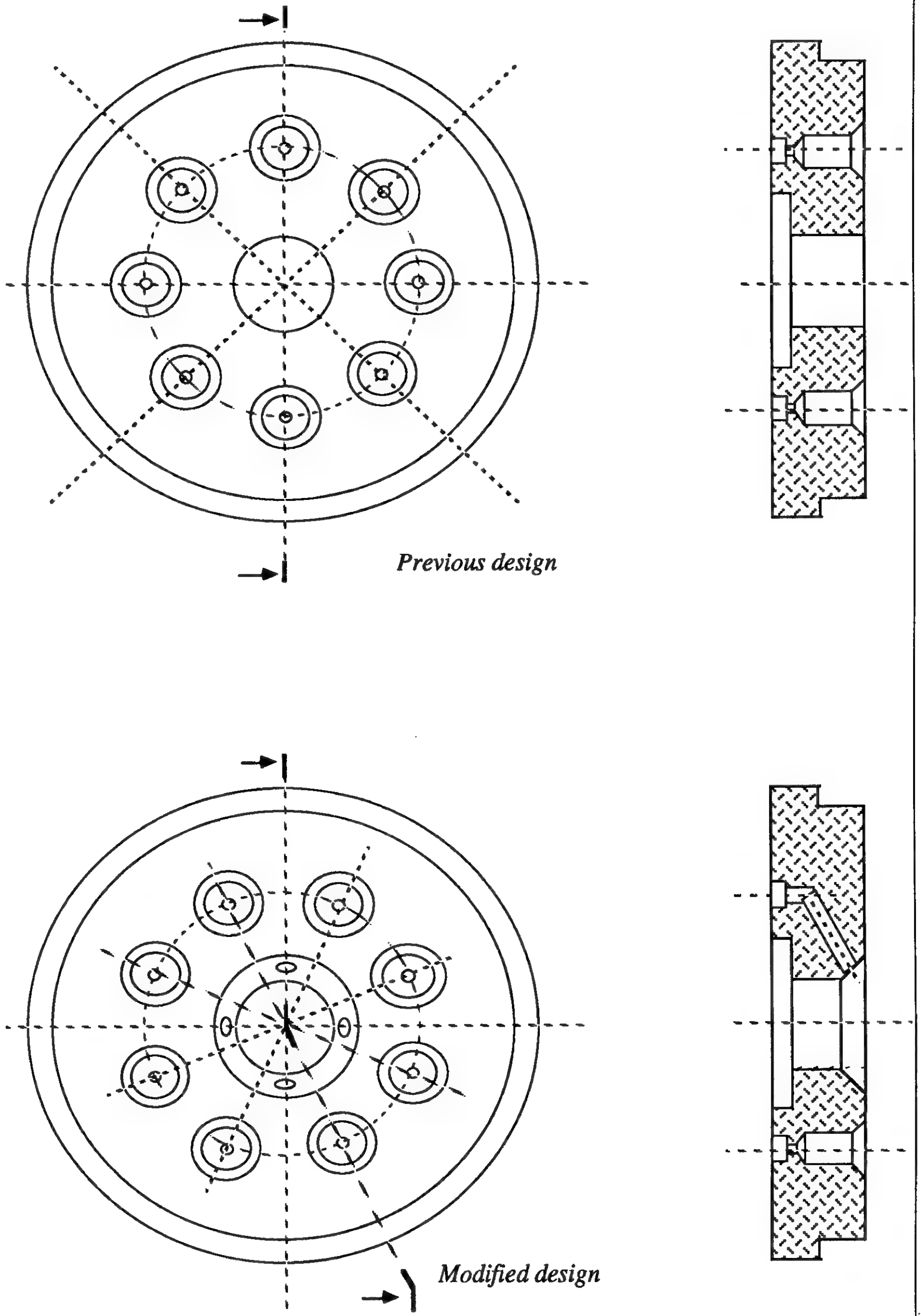


Fig. 2.1 - Boron nitride injection plate modifications

Sec. 3- Mass Flow Rate Measurements

Gas Calibration Method. The first phase of testing consisted in performing the calibration of the gas feeding system. This permitted the determination of:
- the time (in the order of ms) between the opening valve electric signal and the steady state condition of the mass flow rate in the gas pulse; this value is used to set the ignitron activation signal in order to permit the discharge to occur when a steady value of mass flow rate is reached in the thruster;
- the relationship between the steady state value of the mass flow rate and the pressure in the reservoir placed upstream of the solenoid valve (see Fig. A2.1).

The calibration consisted of two phases. In the former the chocking orifices were calibrated, in the latter the delay time and the relationship between back pressure and mass flow rate was found by measuring the opening valve signal and the gas pulse. To this end, a piezo-resistive pressure gauge was placed in the volume behind the chocking orifices.

The calibration of the orifices was performed as follows:
- a mass flow meter was placed in series with the gas feeding system line.
- a vacuum of few mbars was maintained in the vacuum chamber by means of the rotary pump (this vacuum level is sufficient to obtain the chocking condition of the orifices).
- the solenoid valve was opened for a few seconds during which a flow of nitrogen was established in the line; when a steady state condition was attained, both the mass flow rate (with the mass flow meter) and the signal from the pressure gauge were measured. This operation was repeated for a certain number of mass flow values.

The results of the calibration of the orifices is a linear relationship between the nitrogen mass flow rate (mfr_{N2}) and the orifice upstream pressure (P_v).

The second calibration phase was carried out using nitrogen, hydrogen, argon, simulated ammonia and simulated hydrazine as propellants. In this case the solenoid valve is opened with a 10 ms electric pulse of 30 V. During the gas pulse, the pressure in the volume upstream of the orifices was measured together with the electric pulse using the transient recorder, for different values of the reservoir pressure (P_r). By comparing the two signals it was possible to establish the delay time and the relationship between the steady value of the pressure in the volume upstream of the orifices and the relevant reservoir pressure. This procedure was repeated for each gas.

In the case of nitrogen, the relationship between the mass flow rate and the reservoir pressure was derived by putting together the relationships obtained during the orifice calibration and in the second calibration phase. For the other gases, the orifice calibration relationship was modified before this procedure according to the following expressions:

$$mfr_{gas} = mfr_{N2}\,(\Gamma_{gas}\ \sqrt{M_{gas}})\,/\,(\Gamma_{N2}\ \sqrt{M_{N2}})$$

where Γ is the Vandekerkove function and M is the molecular weight of the gas. The following values were assumed:

$\Gamma_{N2,\,H2,\,NH3,N2H4} = 0.697$ $\qquad$ $\Gamma_A = 0.724$

$M_{N2} = 28$ $\qquad$ $M_{H2} = 2$ $\qquad$ $M_A = 40$

$M_{NH3} = 17$ $\qquad$ $M_{N2H4} = 32$

Previous tests carried out with another thruster demonstrated that this method of obtaining the orifice calibration relationship using the values measured for another gas is in good agreement with the experimental results. The difference between calculated and experimental results is not noticeable and is lower than the experimental uncertainty.

Gas calibration results. Fig. 3.1 shows the result of the orifice calibration. No variations were observed repeating the measurements three times. A linear fit of the data gives the following relationship:

$$P_d = 0.89 + 109.27\ mfr_{N2} \qquad (P_d \text{ in mV and } mfr_{N2} \text{ in g/s})$$

Figs. 3.2 - 3.4 shows the electric signal applied to the solenoid valve for the pulsed operation and typical gas pulse signals for the various gases. Again, these signal are very repeatable. Their amplitude is proportional to the resevoir pressure but their shape is independent of pressure. The determination of the time to reach steady the state mass flow condition from the starting of the valve electric signal is obtained by comparing each gas pulse with the valve electric signal. This time is 15 ms for nitrogen, argon and hydrazine and 10 ms for hydrogen and ammonia.

Finally, the dependance of the steady mass flow of the gases on the reservoir pressure is given by the following expressions:

$$P_r = 2.09\ mfr_{N2} \qquad (P_r \text{ in bar and mfr in g/s})$$

$$P_r = 7.81\ mfr_{H2}$$

$$P_r = 1.68\ mfr_{A}$$

$$P_r = 2.68\ mfr_{NH3}$$

$$P_r = 1.96\ mfr_{N2H4}$$

As the repeatability of the results and the linear fits of the data are good, the overall accuracy of the gas calibration is determined only by the accuracy of the various experimental devices adopted. The uncertainty analysis shows that the mass flow rate can be set with an accuracy better than +/- 5% in a range of 0.5 - 3 g/s for nitrogen, ammonia, hydrazine and argon and in a range of 0.1 - 0.5 for hydrogen.

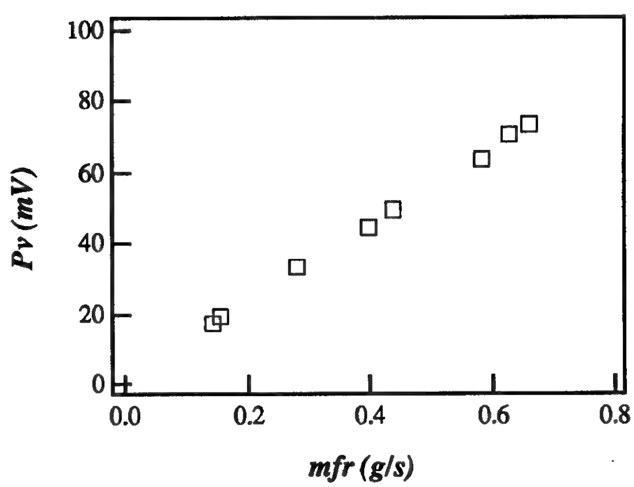


Fig. 2.1 - Orifice calibration results (nitrogen)

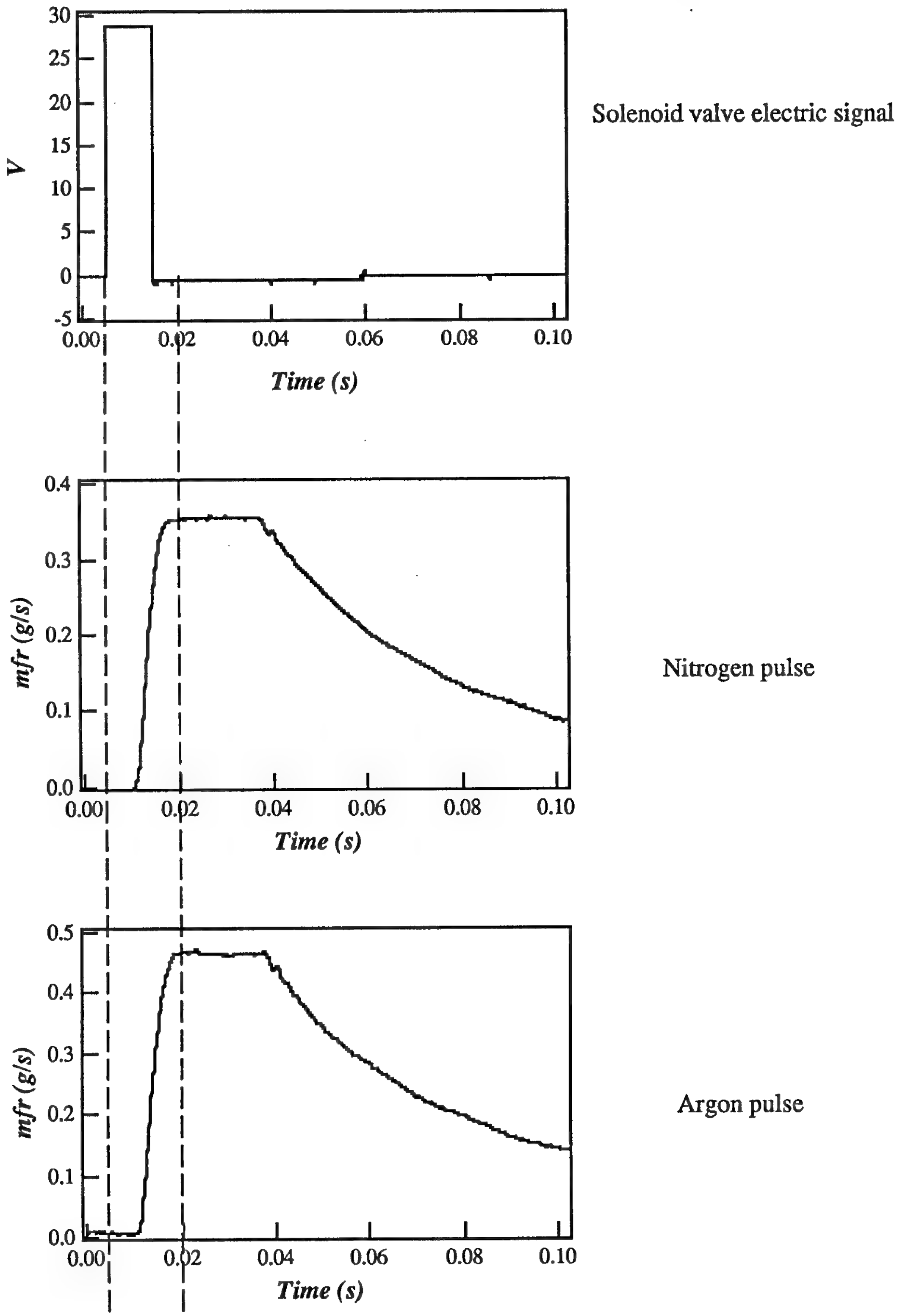


Fig. 2.2 - Comparison between the solenoid valve signal and typical gas pulses (nitrogen and argon)

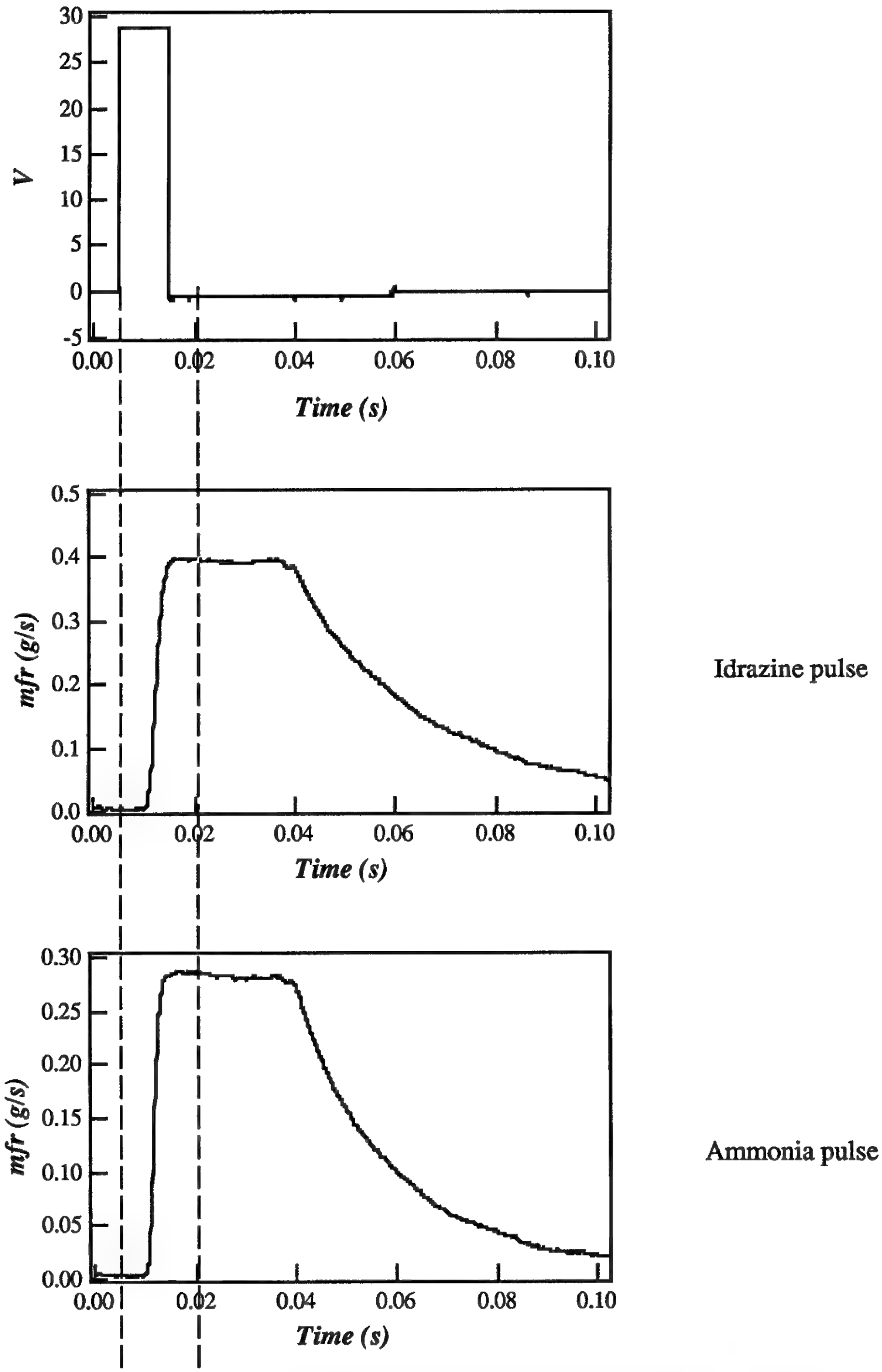


Fig. 2.3 - Comparison between the solenoid valve signal and typical gas pulses (simulated idrazine and ammonia)

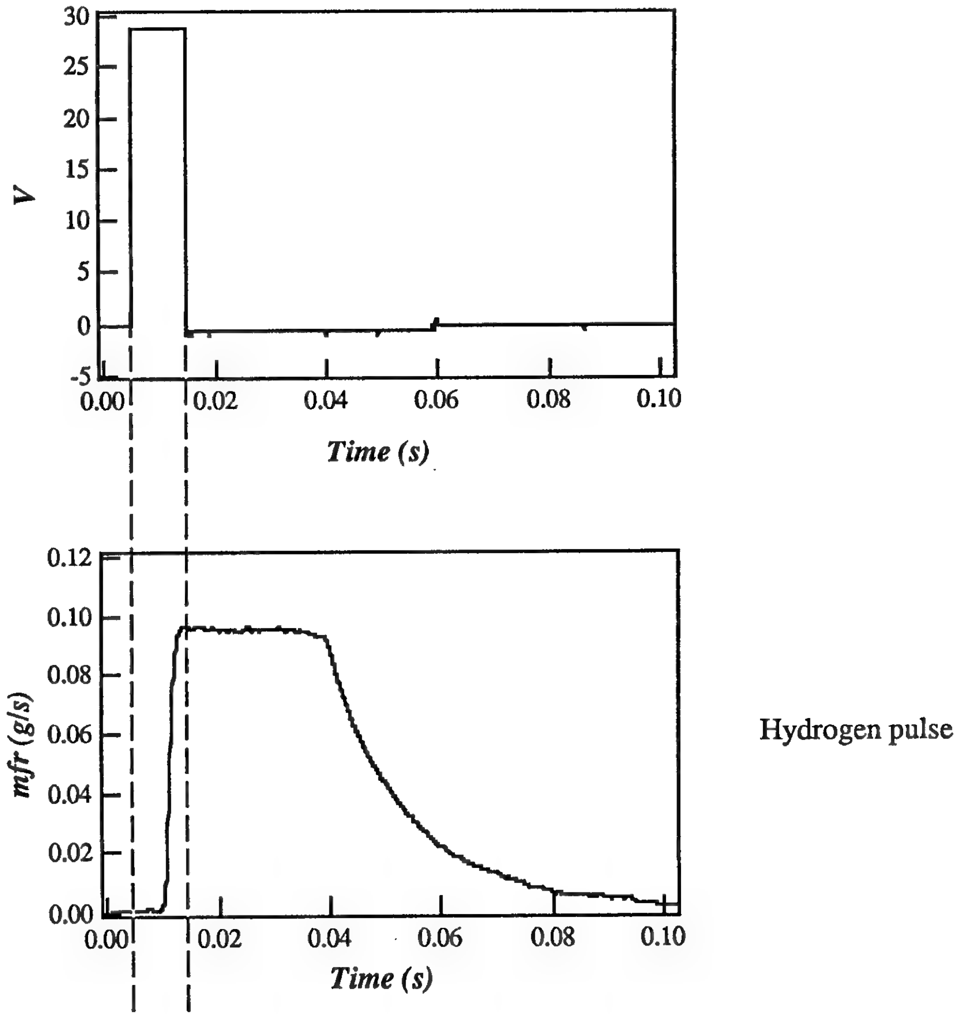


Fig. 2.3 - Comparison between the solenoid valve signal and a typical gas pulse (hydrogen)

Sec. 4 - Electrical Characteristic Measurements

Fig. 4.1 shows the thruster configuration adopted. Two externally identical cathodes were used: one for cold electrode tests and the other for the tests with cathode heating. The external anode surface was covered with a fibre-glass cloth to prevent the electric current from attaching to this surface. The mass flow rate (1 g/s of nitrogen, ammonia, hydrazine and 0.3 g/s of hydrogen) was chosen in order to obtain the full ionization condition at nearly the same current level for all of the propellants.

The test equipment is described in the appendix of the review report 1. The tests were performed in the vacuum chamber, where an ultimate pressure of $5x10^{-5}$ mbar is reached. The discharges were ignited by the ignitron at 15 ms from the starting of the valve electric signal for argon, nitrogen, ammonia and hydrazine and at 10 ms for hydrogen. The pressure in the vacuum chamber during the discharge increased up to about $1x10^{-3}$ mbar.

During the tests with cathode heating, the cathode tip temperature was measured with a pyrometer. The pyrometer was removed by a pendulum just before the discharge (Figs 4.2-4.3). The cathode was heated until to a temperature of 1800 °C (+/- 30°C).

The thruster was inspected frequently during the tests. No signs of anomalous discharge or cathode matherial deposition on the insulator were noticed except at the cathode root, near the cathode injectors. Traces of char were observed on the frontal exit anode surface. Less evident traces were observed on the internal surface for about two thirds of the anode length from the exit plane. On the contrary, the surface appeared polished upstream close to the injector plate. The electrodes and the injector plate were cleaned with acetone during each inspection.

The current was measured with a passively integrated Rogowski coil. It was previously calibrated with a 10 mΩ resistor. The precision of the current measurement is within +/- 3%.

The arc voltage was measured with two high voltage probes (Tektronix P6015). The arc voltage was obtained by difference between the anode voltage with respect to ground and the cathode voltage with respect to ground.

The signals were recorded on the transient recorder HP 5185 and on the oscilloscope HP 54501A and then transferred to a Macintosh computer for analysis and storage.

Each data point shown in the following charts was obtained as follows:

- four (cold test) or three (hot test) readings were made, each for a certain PFN charging voltage.
- for each reading, one value of current and one value of voltage were taken as an average over an interval of 200 μs around the position at 0.5 ms of the discharge (Fig. 4.4)
- each data point was obtained as the average of the four or three values of current and voltage obatined for each PFN charging voltage.
- the bars indicate the dispersion of the results.

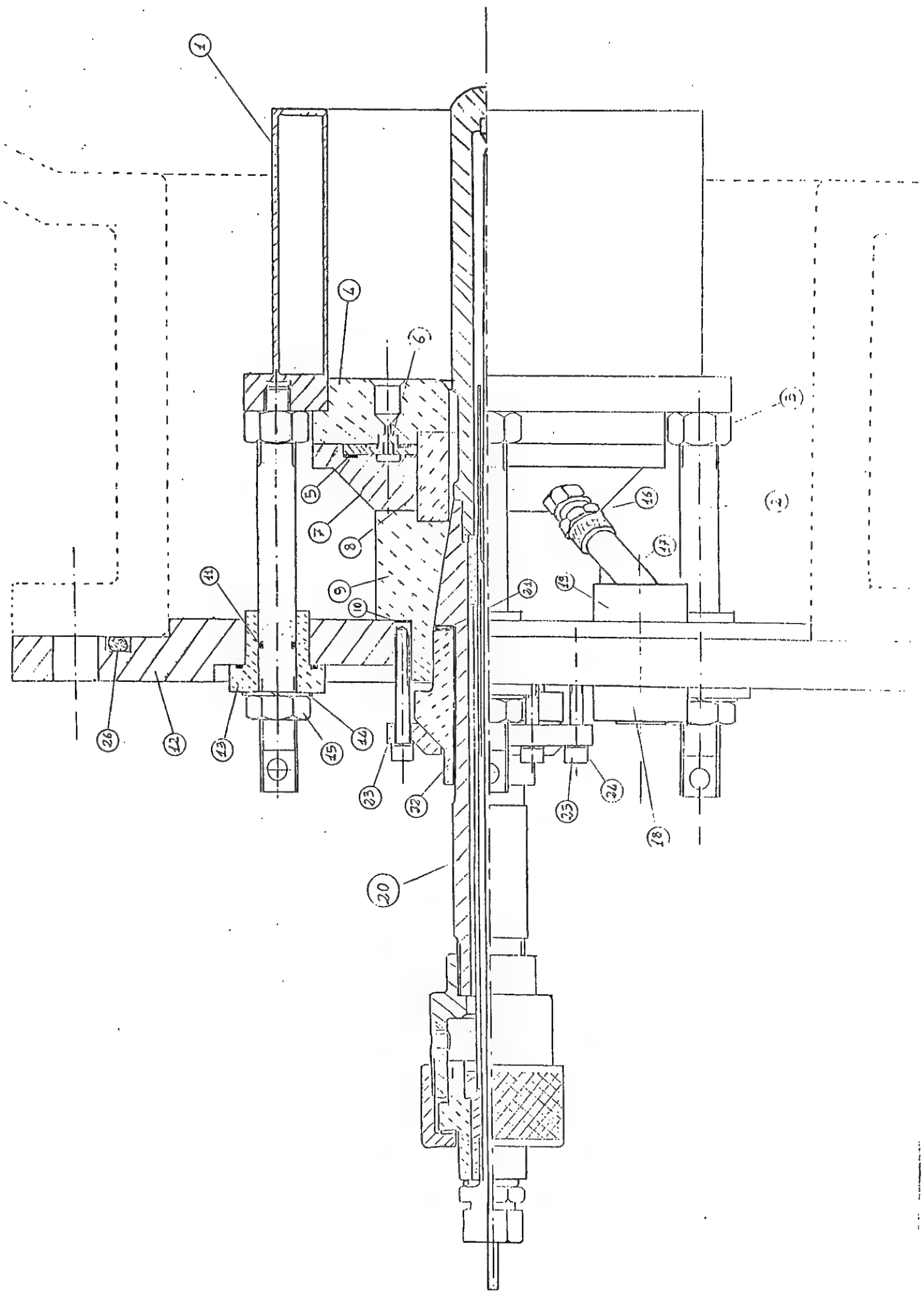


Fig. 3.1 - The thruster configuration investigated

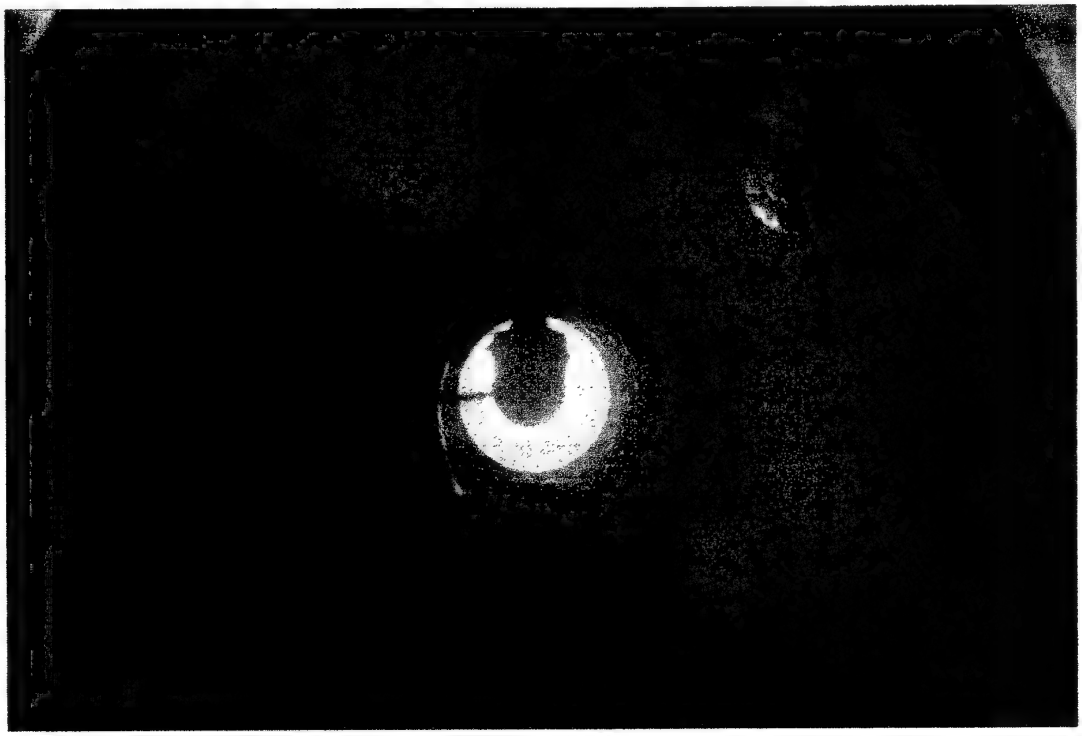


Fig. 3.2 - The thruster during cathode heating (the pendulum placed in front of the cathode)

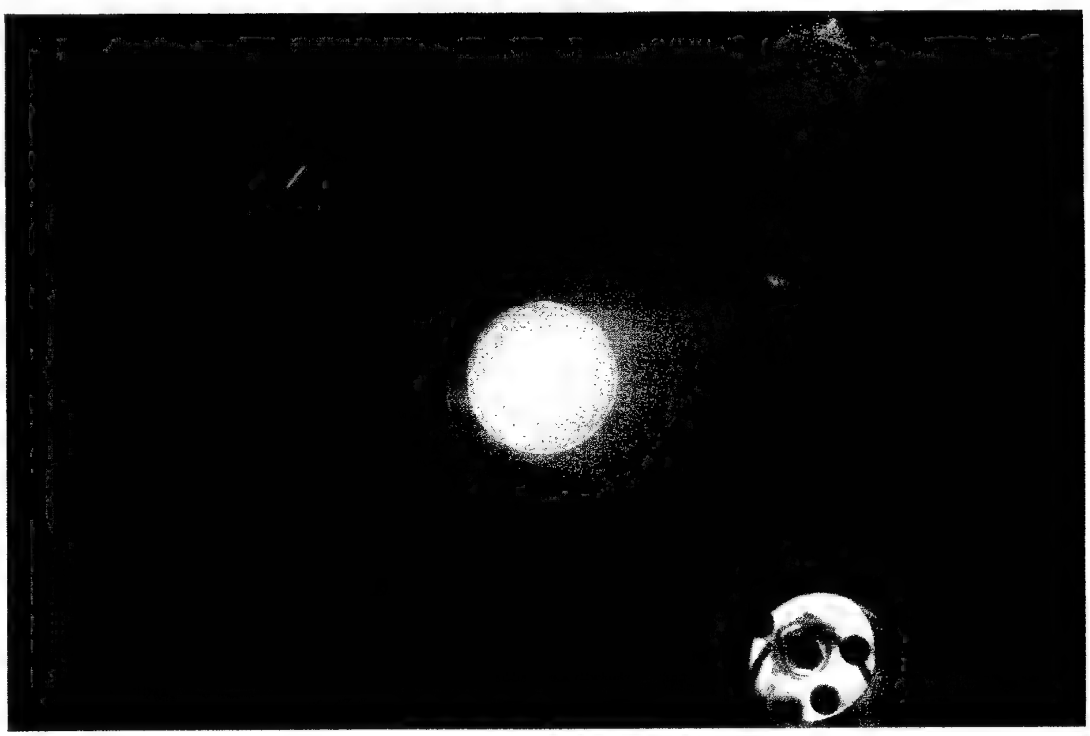
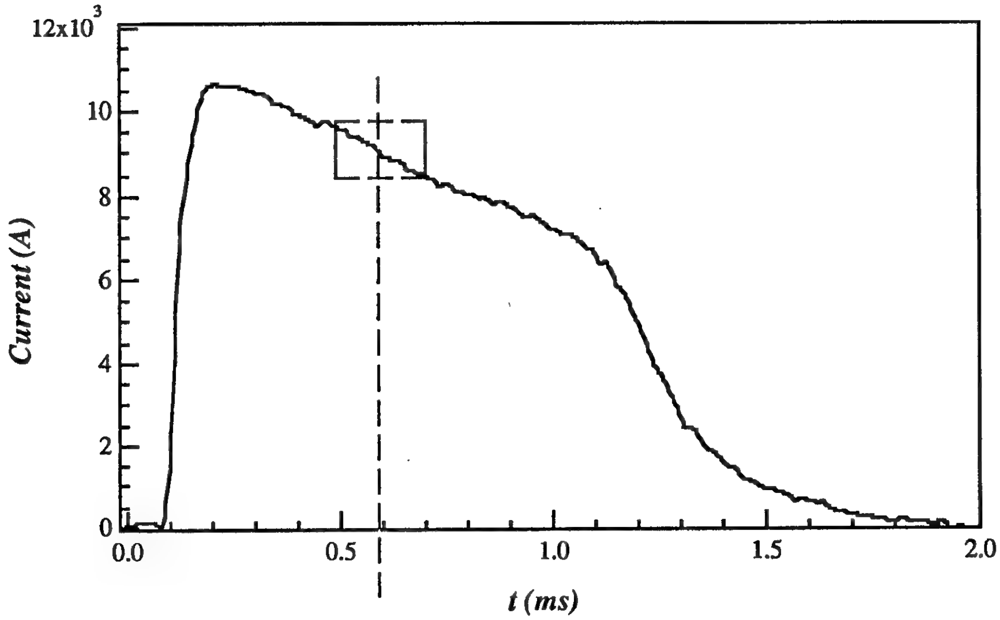


Fig. 3.3 - The thruster during cathode heating (the pendulum removed)



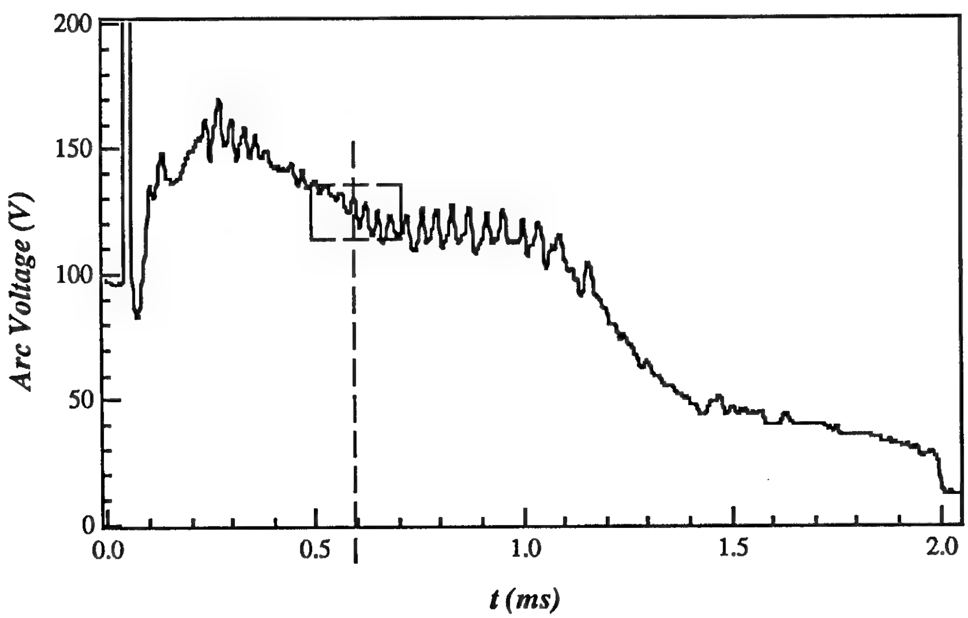


Fig. 3.4 - Typical current and arc voltage signals measured during a discharge

Sec. 5 - Data Analysis and Discussion

For each gas, the comparison between cold and hot cathode operation was carried out in terms of electrical characteristics. Moreover, a comparison between typical arc voltage signals gathered for the two cathode thermal conditions at the same current level is shown.

Nitrogen. In Fig. 5.1 the electrical characteristics with and without cathode heating are compared. The arc voltage with hot cathode is about 15 V lower than the arc voltage with cold cathode at approximately the same current. This difference remains fairly constant in the entire range investigated.The voltage signals gathered with and without cathode heating are characterized by a sort of indentation in the first part of the discharge that becomes larger by increasing the current level (Fig. 5.2). This behaviour was also observed for argon.

Hydrogen. In this case, the arc voltage with cathode heating is slightly lower than the one with the cold cathode (Fig. 5.4). The voltage signals gathered both with and without cathode heating do not present the large irregularities observed with nitrogen and argon. On the contrary, a noise with a frequency in the order of 100 kHz and an amplitude which increases with the current level was observed on all of the signals (Fig. 5.3). This general behaviour was also observed for simulated hydrazine and ammonia.

Hydrazine. The arc voltage with cathode heating is lower than that with cold cathode in the entire current range investigated. The voltage reduction is about 7 - 10 V, an intermediate value between the reductions obtained with nitrogen and hydrogen.

Ammonia. The arc voltage measured with cathode heating resulted lower than the value without heating at current levels lower than 10 kA; the opposite behaviour was observed at higher currents. The observation of the voltage signals at low currents (having digitally filtered the signals to suppress the high frequency oscillations) reveals that the thruster seems to operate in two different regimes, passing from one to the other about every 100 μs about (Fig. 5.9). A regime is characterized by a voltage level about equal to the one measured with cold electrode, the other regime has a lower arc voltage. The thruster seems to oscillate between a situation in which cathode heating has a beneficial effect and a situation in which no significant effects occur with respect to a cold cathode operation. Of course, the understanding of this event, together with the inversion of the electrical characteristics at high currents, needs a more accurate investigation with more extensive test activities.

Argon. Electrical characteristics of argon present an inversion similar to that observed with ammonia. Nevertheless, the inversion seems associated with a pronounced slope discontinuity in the cold cathode electric characteristic at a current level of about 11 kA. This behaviour was confirmed by a subsequent measurement of the characteristic. The thruster seems to operate at a higher mass flow rate than expected; the additional mass could be supplied by an increased erosion rate of the cathode occurring at high current levels.

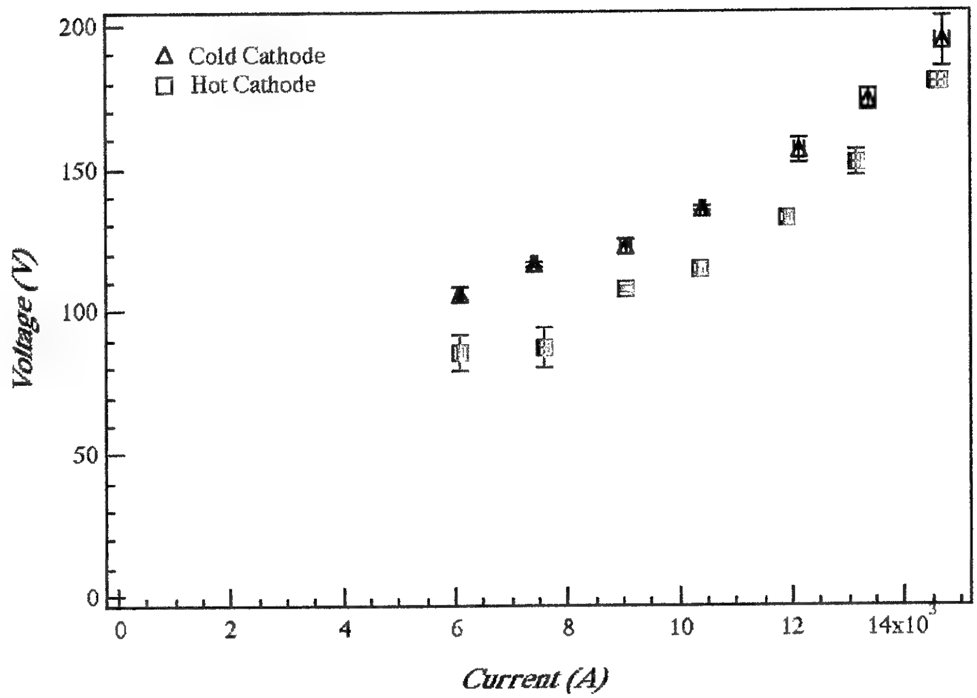


Fig. 4.1 - Electrical characteristic comparison - 1 g/s of nitrogen

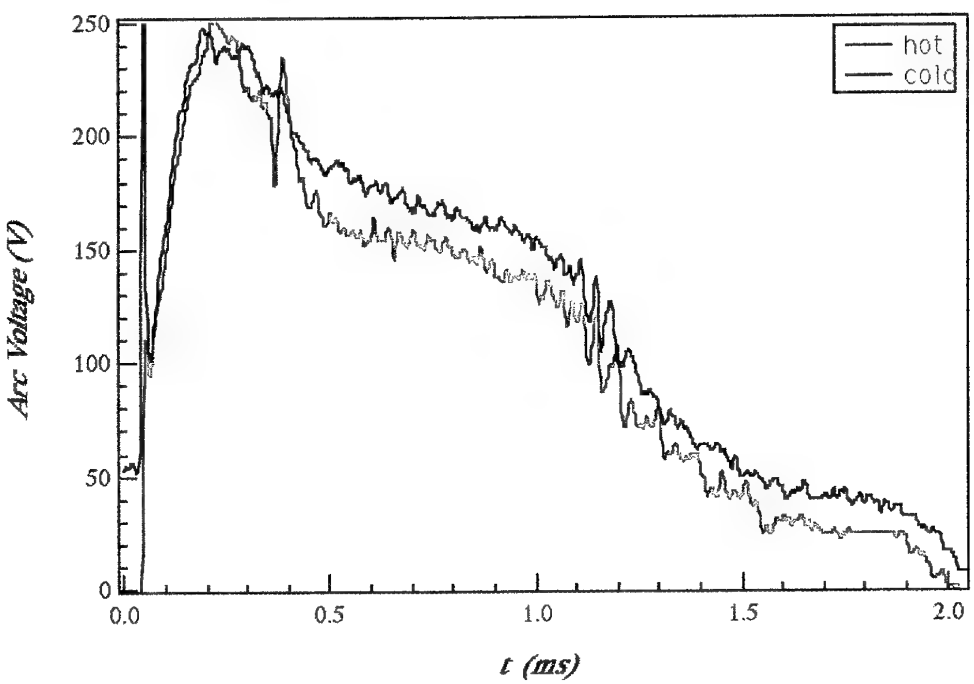


Fig. 4.2 - Arc voltage signal comparison - 1 g/s of nitrogen, 13.5 kA

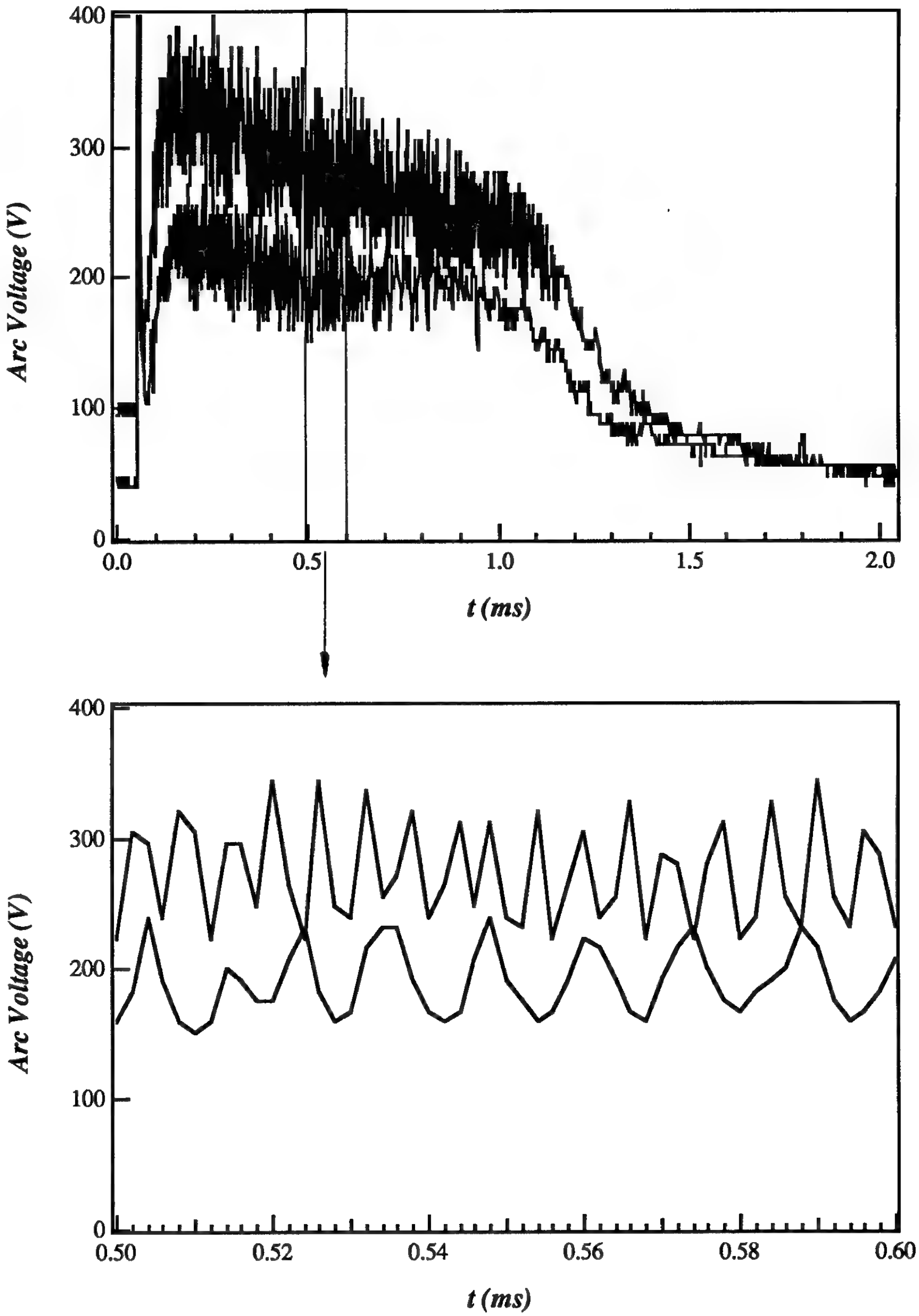


Fig. 4.3 - Typical hydrogen voltage signals - 0.3 g/s, cold cathode, 7 and 11 kA

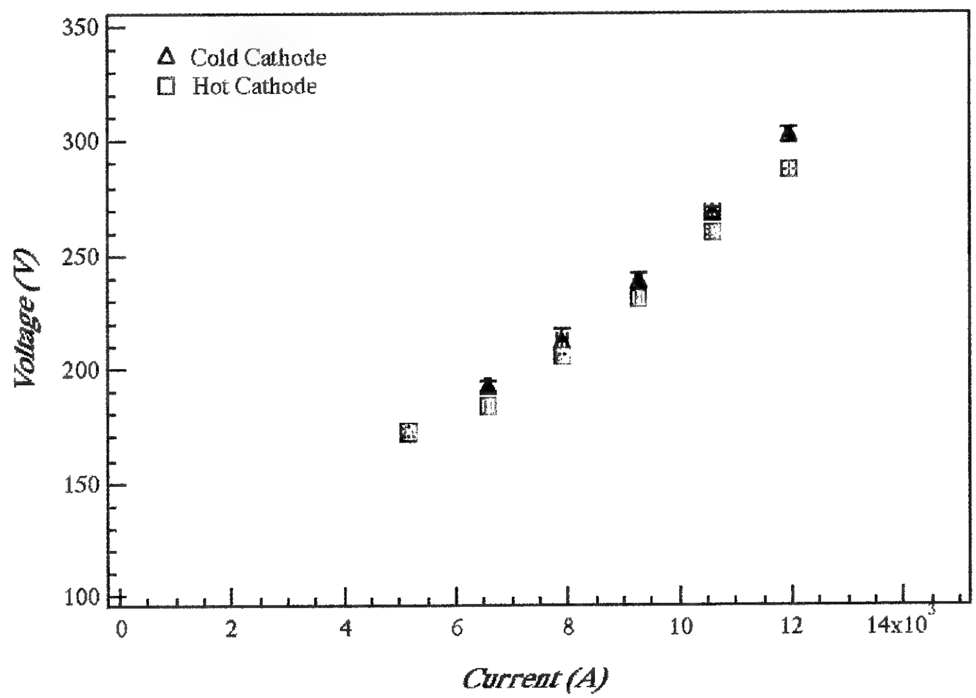


Fig. 4.3 - Electrical characteristic comparison - 0.3 g/s of hydrogen

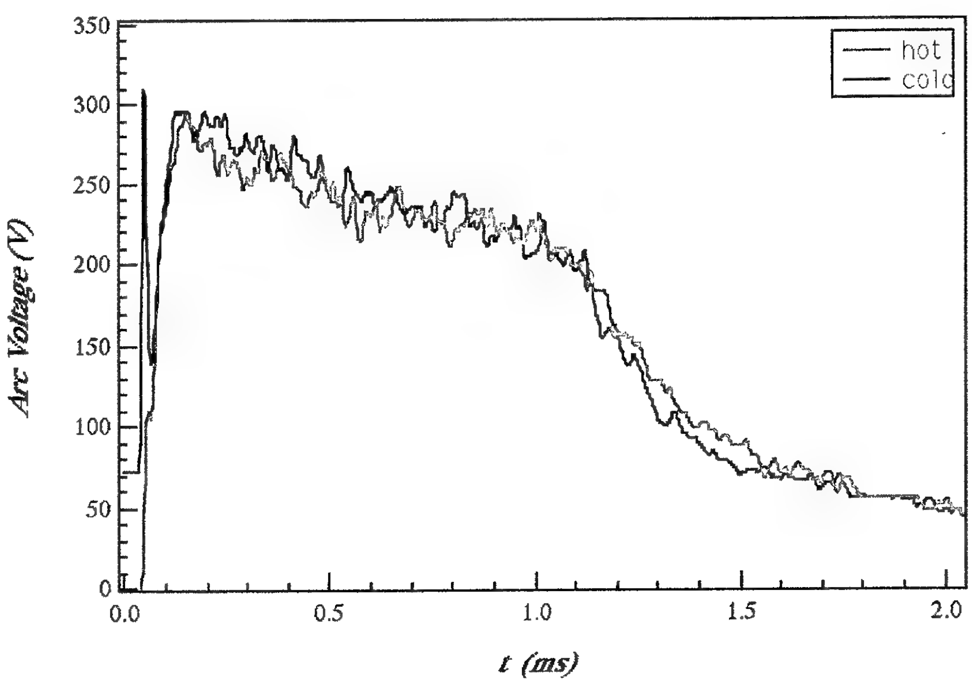


Fig. 4.4 - Arc voltage signal comparison (filtered) - 0.3 g/s of hydrogen, 11 kA

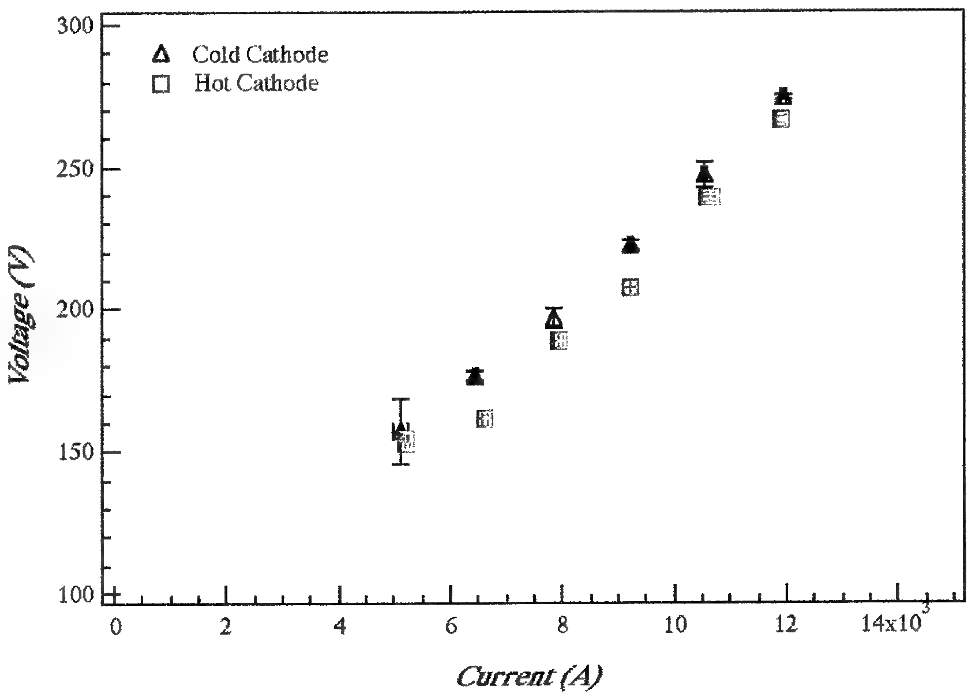


Fig. 4.6 - Electrical characteristic comparison - 1 g/s of simulated idrazine

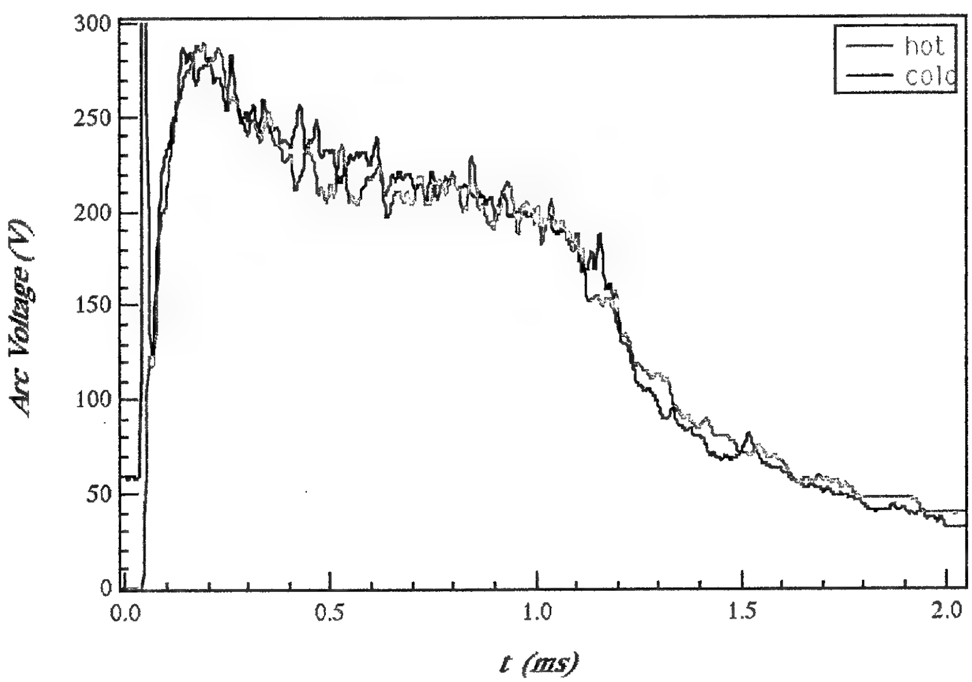


Fig. 4.7 - Arc voltage signal comparison (filtered) - 1 g/s of simulated idrazine, 11 kA

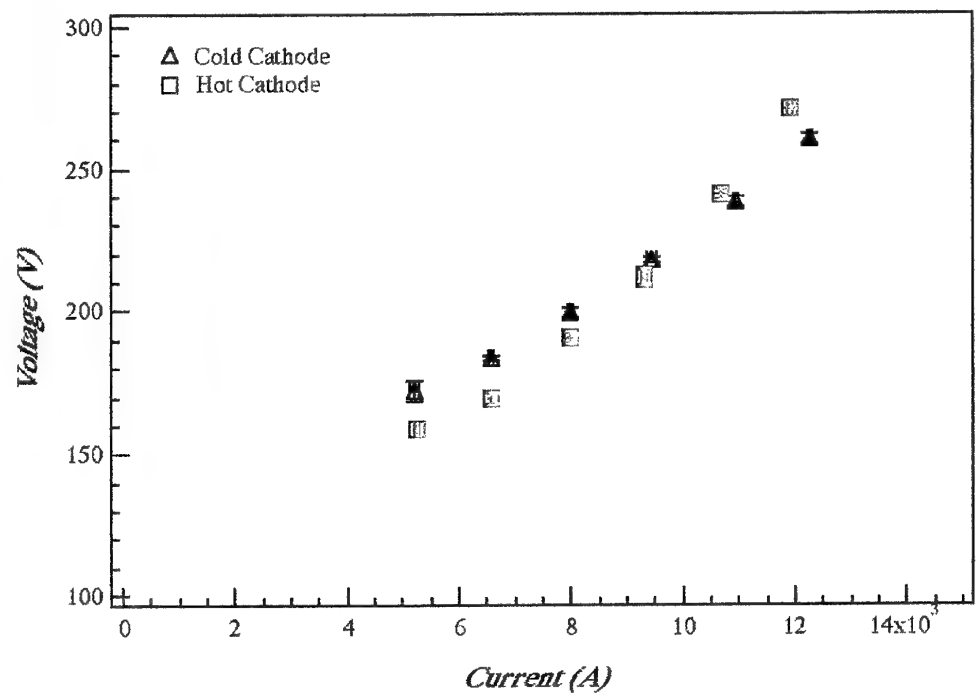


Fig. 4.8 - Electrical characteristic comparison - 1 g/s of simulated ammonia

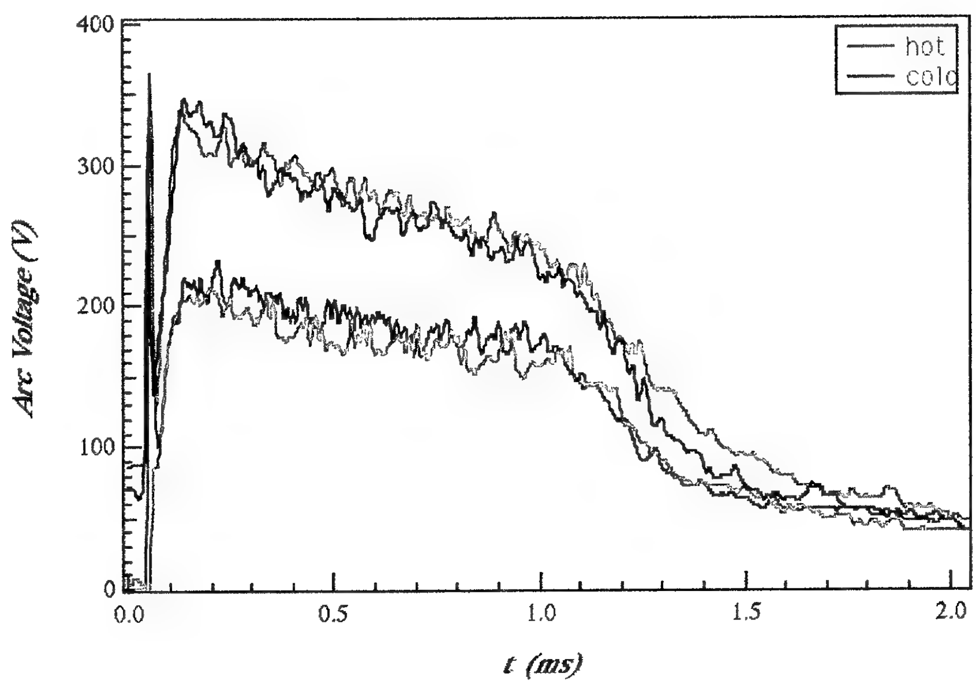


Fig. 4.9 - Arc voltage signal comparison (filtered) - 1 g/s of simulated ammonia, 8 kA and 13.5 kA

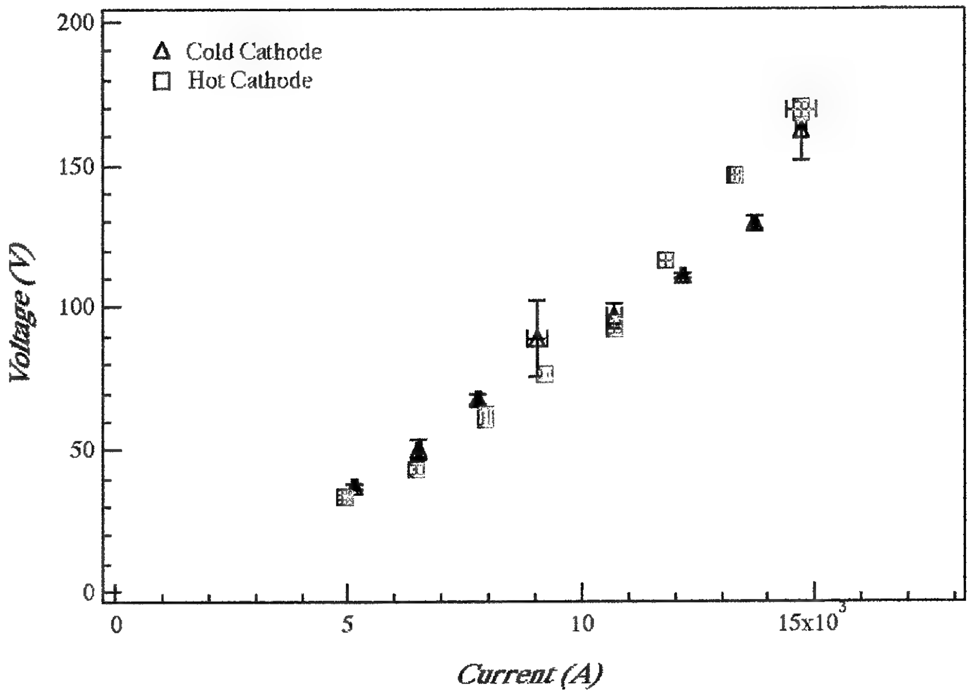


Fig. 4.10 - Electrical characteristic comparison - 1 g/s of argon

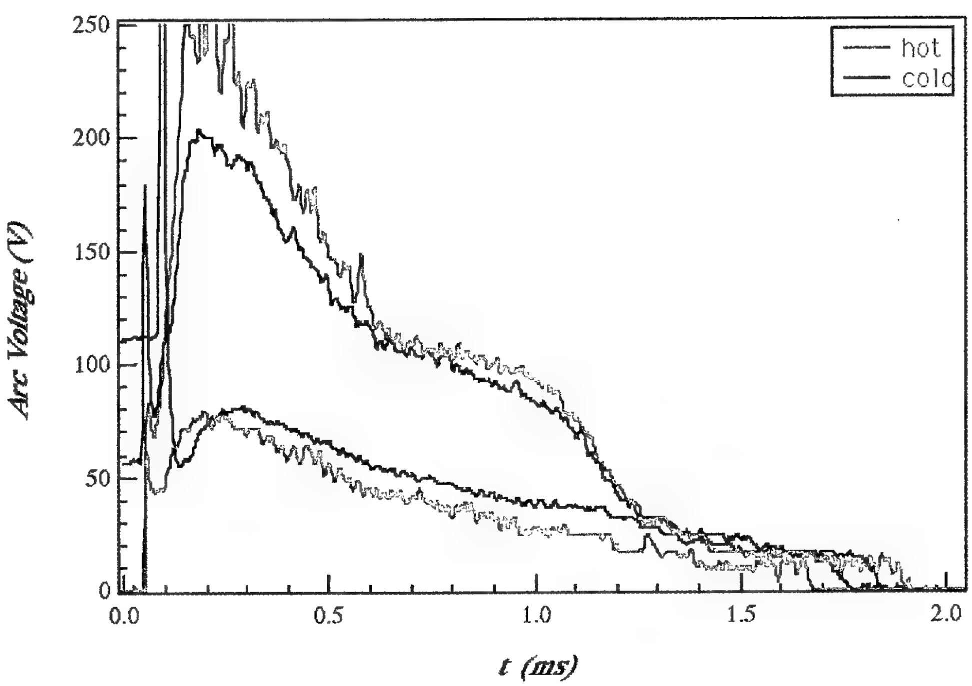


Fig. 4.11- Arc voltage signal comparison - 1 g/s of argon, 6.5 kA and 12 kA

Sec. 6 - Conclusions

The main objectives of this activity were the modification of an AFOSR MPD thruster for testing with a cathode articially heated and the performance of a first series of tests. These tests consisted in the measurement of electrical characteristics with and without cathode heating using different gases as propellants.

After preliminary tests on the modified thruster, some minor but effective further modifications were needed to improve the operation and the robustness of the thruster.

The measurements were then performed on the thruster having a long cathode configuration. More than 100 firings with the cathode heated at 1800 °C and about 150 firings with the cold electrode were carried out.

Even though the current emitted by thermionic effects should be negligible at that temperature, the results gathered seem to indicate that cathode heating has a relevant influence on the thruster operation, although it seems quite strongly affected by the kind of propellant and, probably, by its mass flow rate. A remarkable reduction of the arc voltage with cathode heating was observed with nitrogen and simulated hydrazine. On the contrary, a lower reduction was observed with hydrogen. A different behaviour was observed with ammonia and argon: the arc voltage with a hot cathode is lower at low currents and higher at high currents, with respect to a cold cathode operation. The possible role of cathode erosion at high currents was invocated to explain this occurrence. Nevertheless, an exhaustive explanation cannot be drawn from the amount of data available and additional tests should be repeated and more values of mass flow rate investigated. Moreover, thrust measurements are necessary to comprehensively evaluate the hot cathode effects on thruster performance.

Centrospazio is now involved in a theoretical and experimental activity on the emission and erosion mechanisms of another thruster with the cathode artificially heated before the discharge up to a poor thermionic emission temperature. Plasma quantities near the cathode and current distribution will be measured with and without cathode heating. Moreover, tests to evaluate the influence of the heating on cathode erosion will be carried out. This activity could contribute to a deeper comprehension of the experimental results illustrated in this report.

Appendix 1

Thermal Analysis of the Thruster

A typical testing cycle with cathode heating mainly consists of five phases:
- heater arc ignition (about 1 ms);
- cathode heating and, simultaneously, PFN charging (about 60 s);
- heater arc extinction (about 1 s);
- thruster discharge (about 1 ms);
- vacuum chamber evacuation until working pressure is reached and, simultaneously, cathode cooling by conduction and radiation (about 90 s).

Considering the duty cycle (about 180 s), the thermal stress is derived from the heat supplied by the cathode heater. The heat supplied by the discharge is infact negligible.

Previous experience has shown that the discharge chamber of the thruster must be cleaned after about ten heating cycles, as the cathode heater increases the deposit of char on the thruster (most probably due to the oil from the diffusive pump), which can alter the experimental results. As a consequence, a thermal analysis must demonstrate a safe operation of the thruster for about ten heating cycles.

Anode. The main source of heating for the anode is the radiation from the cathode. To calculate the anode heating the following assumptions have been made:

- the cathode temperature is considered as uniform on the entire external surface and equal to the temperature on the tip (conservative assumption);
- the anode is considered as a black body which absorbs all of the heat radiated by the cathode (conservative assumption);
- no thermal gradient is considered on the anode and its temperature is homogeneous at each time (simplifying assumption);
- the anode is considered as thermally insulated from the other components (conservative assumption).
- the maximum increase of anode temperature for safe operation is considered as $\Delta T = 300$ ºC

As a consequence, the expression adopted to calculate the maximum number of heating cycles (n) compatible with a safe anode operation is:

$$c_a M_a \Delta T = n\, E_{rad} \qquad [1]$$

where:

$c_a = 0.4$ kJ/kg K, thermal capacity of the copper
$M_a = 3.3$ kg, anode weight

and

$$E_{rad} = \sigma A_c \int_0^t \varepsilon_c(T_c)\, T_c(t)^4\, dt \qquad [2]$$

is the energy radiated by the cathode surface ($A_c = 2000$ mm^2), in accordance with the previous assumptions. E_{rad} was calculated numerically using the temperature law shown in Fig. A1.1, that is the cathode tip temperature measured by the pyrometer during a typical heating cycle on the ESA thruster (heater power: 1.4 kW). The cathode emissivity (ε_c) law (tungsten),

shown in Fig. A1.2, was obtained from data sheets (Metallwerk Plansee GmbH "Tungten").

Here, E_{rad} is about 25 kJ, representing about 35% of the entire energy supplied by the heater during each heating cycle (70 kJ).

From [1], the maximum compatible number of cycles is about 16, that is, sufficiently greater than 10. As a consequence, the anode is able to operate correctly without a cooling system.

Insulators and gas injection group. From the thermal point of view, the most critical component is the teflon tube, fixed at the dispenser by means of a swagelock. It means that its temperature must be below 200 ºC after ten heating cycles.

The boron nitride insulators and the gas injection group are heated by:

- the anode by conduction (detail 4)
- the cathode by radiation (details 4 and 8) and by conduction (details 9, 21-22).

Essentially, they transfer all of the heat to the alluminum flange (12), where it is dissipated by the cables and the atmosphere. We assume that the heat transfer towards the alluminum flange is negligible during the ten heating cycles and that those components are homogeneously heated (conservative).

The heat from the anode is negligible. In fact it is almost all transferred throughout the four copper stay - bars, each having about 1000 times the thermal conductivity of the backplate.

The heat from the cathode by radiation is calculated assuming a temperature on the cathode root similar to the cathode tip, but with a maximum of 1500 K (found assuming a linear gradient of temperature from the cathode tip and the back of the heater at ambient temperature). The calculation yields to about 9 kJ of energy for each heating cycle, that is about 12% of the total energy supplied by the heater (70 kJ).

The percentage of heat transferred to the detail 9 from the cathode by conduction can be estimated by comparing the thermal conductivity of the back of the heater with the conductivity of the boron nitride piece. The conductivity of the first is estimated about 10 times that the second. As a consequence, 1/10 of the heat that flows back (about 55% of the total) is transferred to the component 9 from the cathode, while the heat transferred to the component 22 is about 1/50. These two contributions represent about 6 - 7% of the total energy. As a result, it is reasonable to assume that 20 - 25 % of the heat supplied by the heater is dissipated on the BN insulators and on the gas injection group. It corresponds to about 175 kJ of thermal energy supplied in ten heating cycles. The entire thermal capacity of those components being about 1.3 kJ/K, the final temperature is about 150 ºC, which is less than 200 ºC, that is the maximum allowable.

The cathode and the cathode heater. It was designed to support very high temperature (up to 3000 K). In fact the critical components are made of refractory materials (tungesten, boron nitride, allumina), while the components on the back are of stainless steel, where the thermal requirements are less demanding.Moreover, the heat can easily flow throughout the electrical connection and dissipate through the cables and the atmophere.

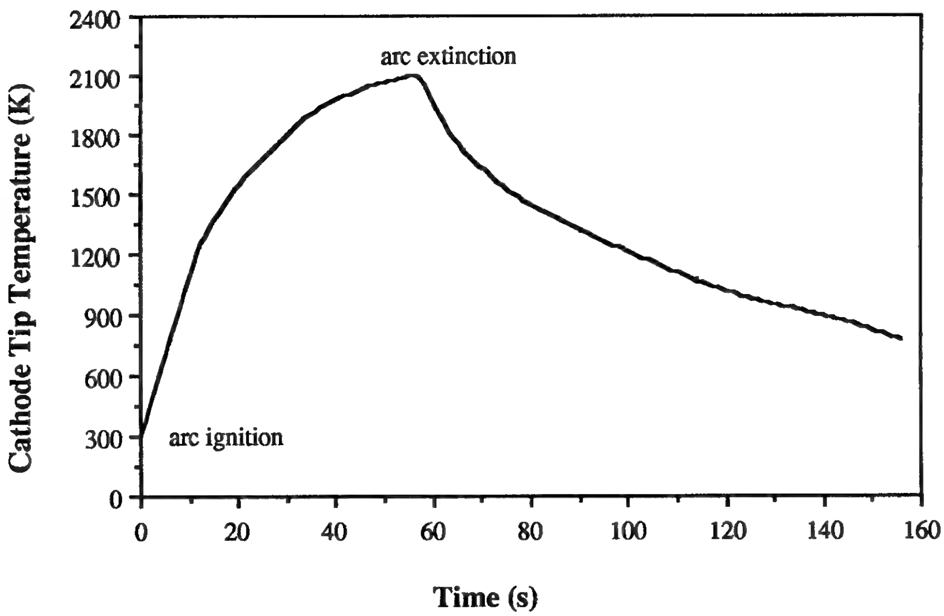


Fig. A1.1 - The cathode tip temperature measured by the pyrometer during a typical heating cycle

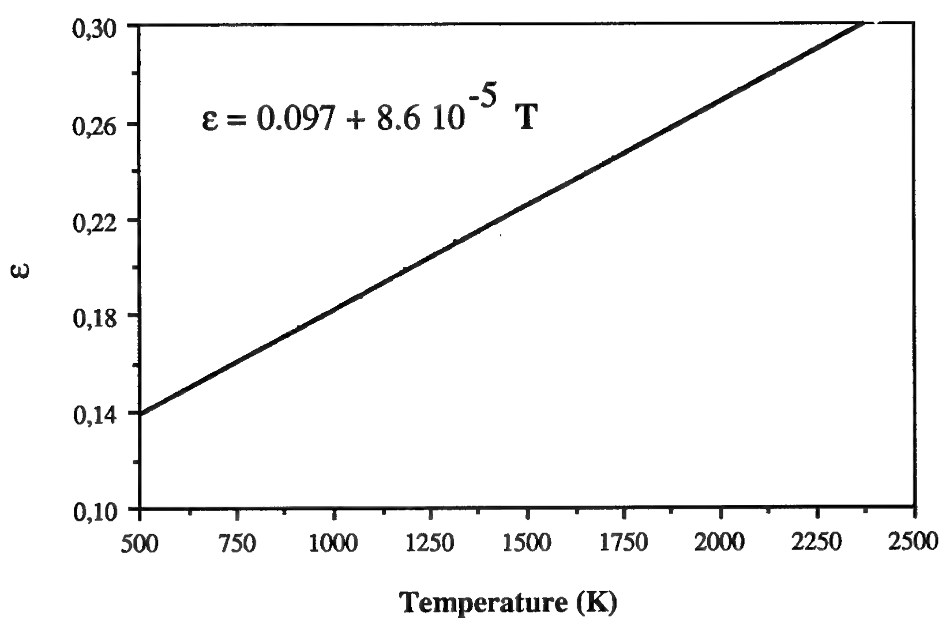


Fig. A1.2 - Thoriated tungsten emissivity vs temperature (from Plansee data sheet)

Appendix 2

Equipment available at CENTROSPAZIO for Testing on MPD Thrusters

The Vacuum Plant. The Vacuum Facility (IV2) consists of a fibre-glass chamber 800 mm in diameter and 1000 mm in length; the dielectric chamber permits testing on MPD thrusters without significant electromagnetic interference. The pumping system consists of a rotary pump for the rough vacuum (Balzers mod. DUO 170) and an oil diffusive pump for the high vacuum (Balzers mod. DIF 500). The ultimate vacuum allowed is 2 10^{-5} Torr with a pumping speed of 6500 l/s. The pumping system is connected to the fibre-glass chamber by a Balzers PVA 500 P gate valve. The pressure is controlled by two Pirani probes (mod. TRP 010), one placed in the vacuum chamber for the rough vacuum measurement, and the other in the diffusive pump to check the pressure before the oil-heating phase. High vacuum is measured by an ionization probe placed on the vacuum chamber (mod. HV 5).

The vacuum facility is manually controlled. A vacuum cycle consists of three phases. During the preliminary phase, lasting approximately 1 hour, the diffusion pump is evacuated and the oil is heated. When the diffusion pump is ready, the plant is set manually for the pumping phase (phase 2) during which the rotary pump evacuates the chamber until a pressure of about 0.1 Torr is reached; upon reaching this pressure, the rotary pump is automatically bypassed again on the diffusion pump, the gate valve is opened and the diffusion pump evacuates the chamber until an ultimate pressure of about 4-3 10^{-5} torr is reached (phase 3).

The Electrical Feeding System. The electrical feeding system consists of a Power Supply, a Pulse Forming Network (PFN), a 40 mΩ ballast resistor, an Ignitron and relative control unit and ten RG8 cables from the PFN to the thruster.

The Power Supply (HVL series 311-6203) has a charging rate of 600 J/s, a peak voltage of 2500 V and is used to charge the PFN before each thruster operation.
The PFN has an internal impedance of 40 mΩ, a total pulse length of 1 ms and stores 3.6 kJ at 2400 V. The total capacitance is 12500 μF, the total inductance 20 μH. The PFN is made up from ten sections, each containing 180 capacitors of 75 μF each and 180 coils of 1 μH each.

The PFN supplies a quasi-rectangular 1 ms current pulse up to 30 kA under normal operating conditions.

The PFN is equipped with a Dump Switch which allows the discharge of the PFN on an appropriate resistor.

The ballast resistor is used in order to match the internal impedance of the PFN with the external impedance, in order to obtain a rectangular current pulse from the PFN. The ballast was designed and manufactured by CS. It can be set from 0 to 40 mΩ and can stand currents of up to 50 kA for 1ms every 30 s without failure.

The ignitron is an electronically-controlled spark gap which permits discharge at a proper adjustable delay from the beginning of the gas pulse, when a steady state condition is reached. The ignitron used is a National electronics inc mod. NL1037. An electronic ignition system was developed in order to control the spark gap ignition with a programmable delay.

The Gas Feeding System. The gas pulse is supplied by solenoid valve(s) (SMC mod. EVT 317), placed as closest as possible to the injection plate(s). A reservoir is placed back to each valve in order to keep a steady pressure during the gas pulse. This is necessary to obtain a sufficiently long steady phase of the mass flow during the pulse. The gas is supplied to the reservoirs from a panel where two gases can be handled. The gases arrive from the high pressure bottles after a first pressure reduction, at a pressure of up to 20 bar. Four tanks are placed on the panel, three are used as pressure tanks (two for the thruster and one for the cathode heater) and one is used to compose the gas mixtures. A pressure gauge is placed on each tank . The tank for the cathode heater is filled with Argon, the pressure of which is maintained at about 1 bar. The pressure on the thruster injection lines can be set by means of two reducers for each line, mounted in parallel, to be used alternatively, depending on the setting pressure. In fact, the reducers have two different ranges (0 5 - 8.5 bar and 0.05 - 2 bar) to set the gas pressure (and, as a consequence, mass flow rates) at low and high values with the desired precision. The gas mixture can be composed in the dedicated tank, supplying alternatively the gases from the high pressure line. The composition of the mixtures is controlled by a pressure probe placed on the tank. The mixture can thus be supplied to the anode and/or the cathode injection line through the reducers described above, bypassing the line from the high pressure bottles. In order to purge the lines before testing, they are provided with venting lines linked to the vacuum chamber. The gas feeding system operation is currently manual, but could easily be automated in further activities.

The Cathode Heating Apparatus.The cathode heating apparatus consists of a TIG power supply (CETASS CM 520) equipped with a high voltage ignition system (developed in CENTROSPAZIO) and a series of contactors, necessary to properly perform the test sequence (cathode heating, PFN charging and firing). The electrical set-up, illustrated in Fig. A2.1, consists in two electrical networks with a common electrode (the thruster cathode). When the thruster is ready for discharge, three properly-delayed contactors are activated: the first one disconnects the heating power supply, extinguishing the inner arc. The second contactor disconnects the power supply electrodes from the thruster, the third one disconnects the PFN charging power supply from the discharge network and then the thruster is fired. The entire sequence is carried out in a few fractions of a second, during which the cathode thermal condition remains practically unchanged.

Pyrometer Moving System. The cathode temperature during the heating phase is controlled by a pyrometer, placed on the thruster axis, in front of the cathode tip (Fig. A2.2). Before each shot, the pyrometer is moved into a safe position by a moving system, in oder to prevent the pyrometer from being contaminated by the plasma exhaust. The moving system is a pendulum, attached to the PVC framework by a PVC chase. The arm is moved from measuring position (vertical arm) to the safe position (with an inclination of about 60°) by a synchronous motor. The positions are defined by two limit switches. The pendulum can be adjusted both vertically and horizontally in order to position the pyrometer correctly with respect to the thruster. The pendulum moving sequence is the following:
- The arm is brought to vertical position, the pyrometer is ready for temperature measuring;
- The heater arc is ignited, the cathode is heated to the desired temperature (read by the pyrometer);

- The arm is moved until the safe position is reached;
- The discharge sequence is performed;
- After firing, the arm is moved to the measuring position and the entire sequence can be repeated.

The Diagnostic Equipment. The following diagnostic facilities are normally used for calibrations, electrical characteristic and thrust measurements, following the procedures developed in the framework of previous programmes. Considering the reliability demonstrated in the previous activities and staff experience on these devices, they were adopted entirely for this programme too.
The diagnostic equipment consists of :
- a mass flow meter (Micro Motion mod. D6) used for the mass flow rate calibration;
- two piezoresistive pressure gauges (Kulite mod. HKM-375-250-G) used for the mass flow rate calibration;
- two high voltage probes (Tektronics P6015 1000X) for electrode voltage measurement;
- an operational amplifier (Tektronix AM 501) used for voltage measurement;
- a Rogoswski coil passively integrated for the current measurement;
- a proximity transducer (Bently Nevada mod 7200) for the measurement of the mobile mass displacement of the thrust stand;
- a pyrometer (Accufiber mod. 900-PY-HF1) to measure the cathode tip temperature.

The Thrust Stand. The thrust stand used was designed and manufactured at CS within a previous ESA ASTP3 programme. It consists of a mobile mass (on which the thruster is mounted) supported by four bars, each one with two phosphor bronze virtual hinges at the extremity. The thrust stand has a four bar linkage configuration, with one degree of freedom in the direction of the thrust, that is measured by detecting the horizontal displacement of the mobile mass immediately after a discharge by the proximity transducer. This permits to measure the impulse of the thrust and thus the instantaneous value of the thrust, if its time law is known. Fig. A2.3 shows the thrust stand assembly with a thruster mounted.

The Probe Positioning System. In the framework of plume diagnostics activities with electrostatic (Langmuir) and magnetic probes, a positioning system, made of PVC, was designed and manufactured. This device allows the probes inside the vacuum chamber to be placed and moved for the measurement of the physical quantities of the plume (temperature, density, magnetic field). Moreover, the device developed was also used successfully for Laser diagnostics with only minor modifications. The positioning system provides three degrees of freedom in accordance with a cylindrical reference system. The design allows further degrees of freedom to be added for future experimental requirements. The system is illustrated in Fig. A2.4. It permits the probes placed in the centre of the wheel to cover a cylinder of 300 mm in diameter and 480 mm in length. The system is moved by three step motors, one for each degree of freedom. Even if the structure is quite heavy, positioning and repeatibility errors are mainly caused by the PVC buckling rather than the step motor accuracy and the manufacturing precision. Moreover, a repeatability of less than +/- 1mm is normally obtained.

The Data Acquisition System. The data acquisition and analysis system consists of:
- A transient recorder HP 5185 where the diagnostic signals are monitored and digitalized.
- The Macintosh IIvx computer, where data are transferred from the transient recorder via a IEEE 488 paralel gate.

Data are managed by means of LabView® programme for visualization, digital filtering and other analysis operations. The data are then normally stored in the computer hardisk or on floppy disks. It is possible to transfer selected data directly onto dedicated files for graphics, tables etc, that can be used for data reporting.

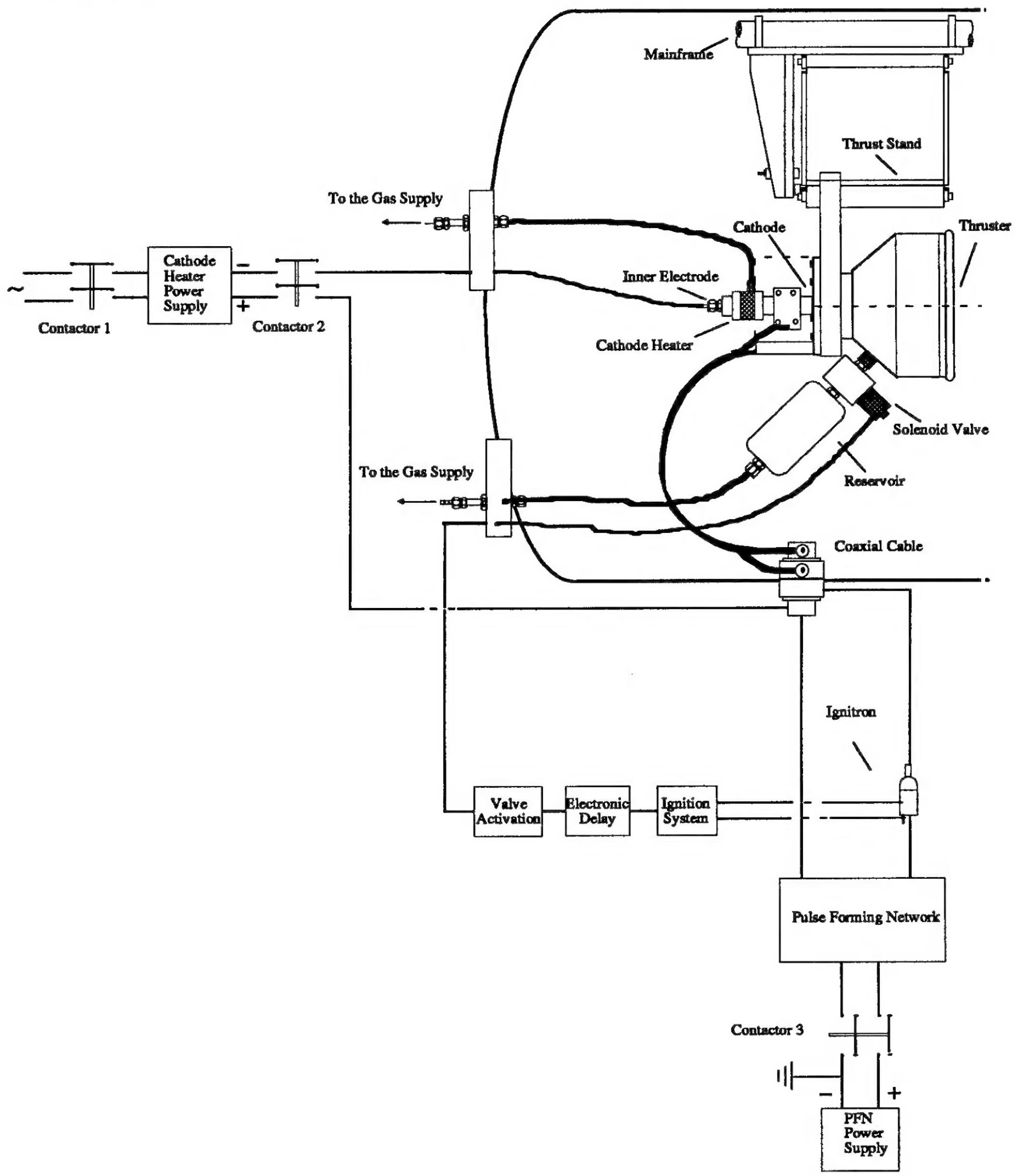


Fig. A2.1 - Test Equipment

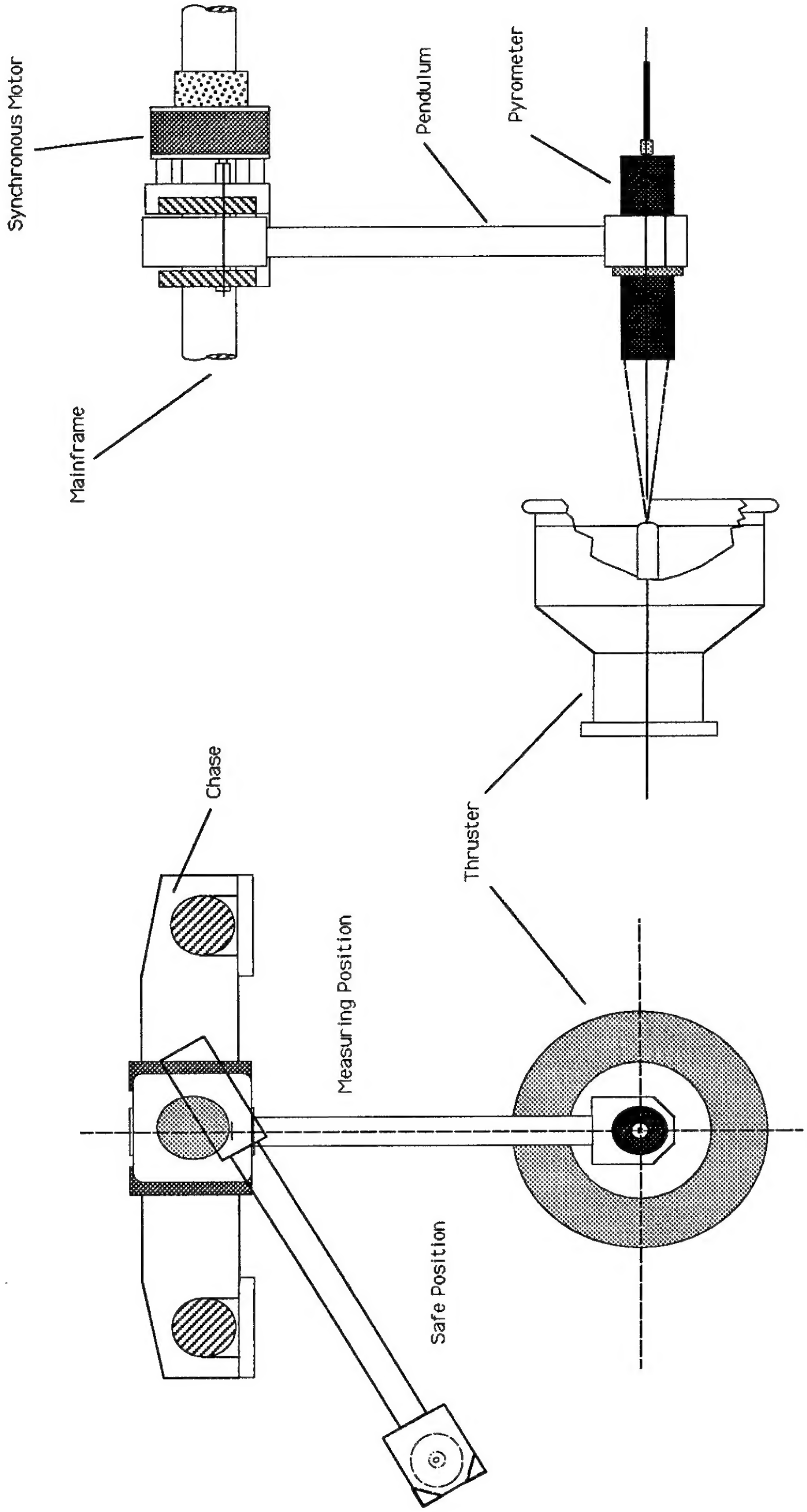


Fig. A2.2 - The Pyrometer Moving System Arrangement

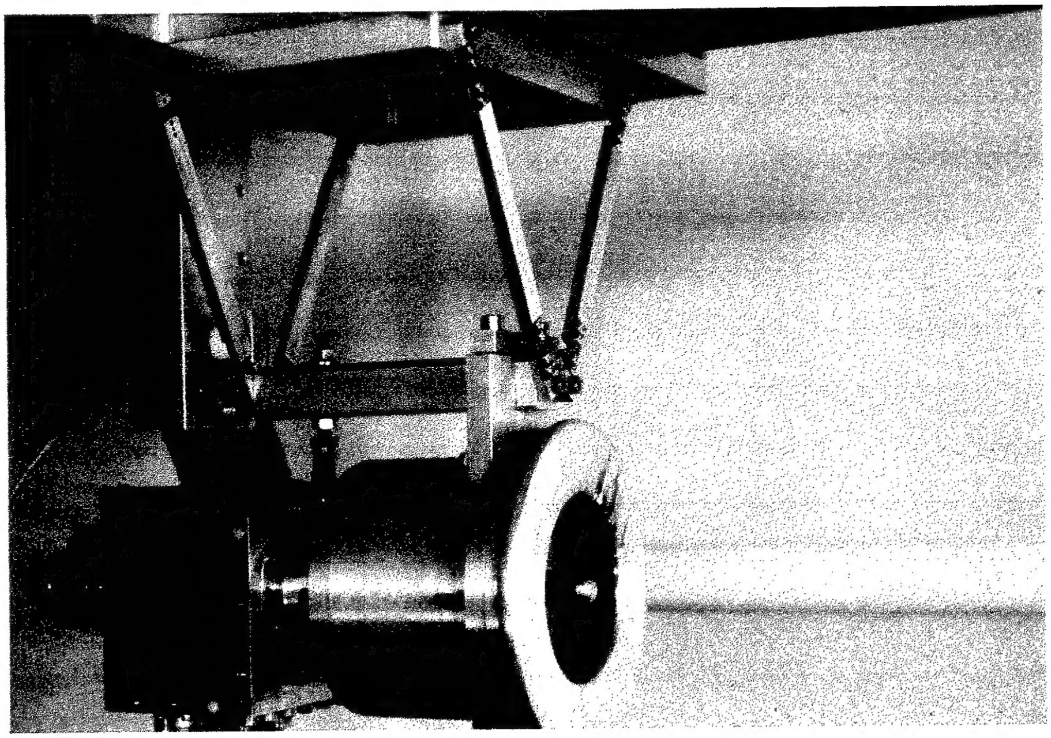


Fig. A2.3 - The thrust stand with a thruster

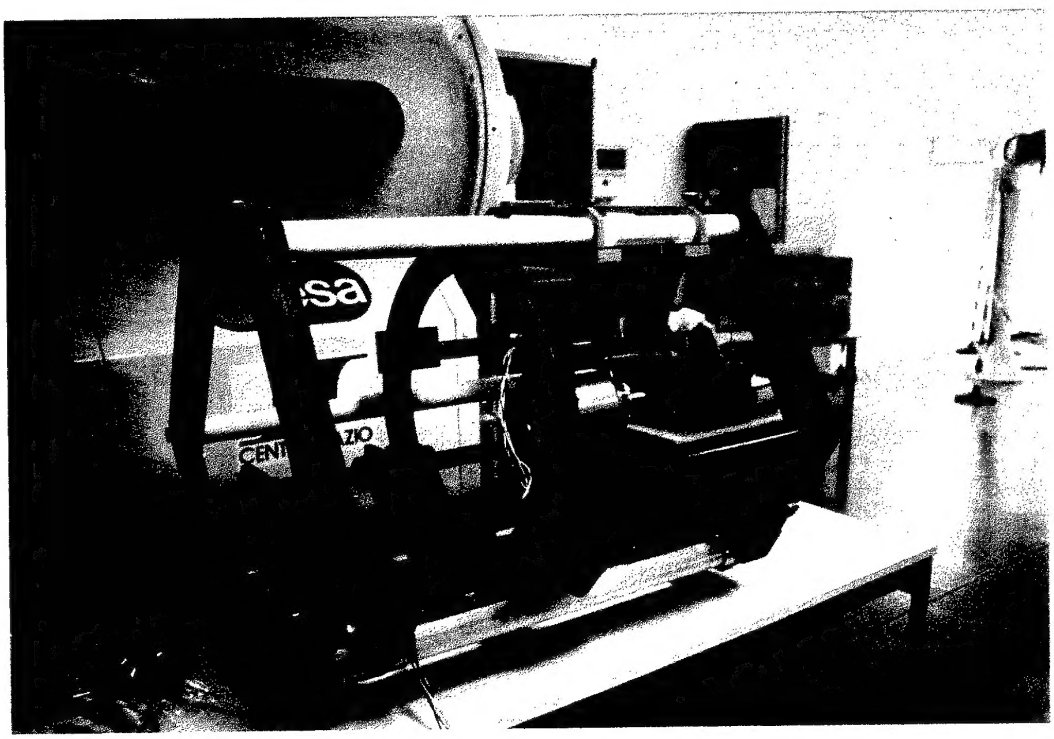


Fig. A2.4 - The probe positioning system